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CONTENTS.

MEETING AT NEW YORK, JANUARY 14, 1916

Outline of Theory of Impulse Currents—By Charles P. Steinmetz... 1

MEETING AT NEW YORK, FEBRUARY 8 AND 9, 1916.

The Municipally-Operated Electrical Utilities of Western Canada—By A. G. Christie... 33
Crest Voltmeters—By C. H. Sharp and E. D. Doyle. (*Illustrated*)... 99
The Crest Voltmeter—By L. W. Chubb. (*Illustrated*)... 109
The Voltmeter Coil in Testing Transformers—By A. B. Hendricks, Jr... 117
Notes on the Measurement of High Voltage—By William R. Work (*Illustrated*)... 119
Operation on the Norfolk and Western Railway—By F. E. Wynne. (*Illustrated*)... 147
The Liquid Rheostat in Locomotive Service—By A. J. Hall. (*Illustrated*)... 167
Chattering Wheel Slip in Electric Motive Power—By G. M. Eaton. (*Illustrated*)... 175
A Method of Determining the Correctness of Polyphase Wattmeter Connections—By W. B. Kouwenhoven. (*Illustrated*)... 183
The True Nature of Speech—By John B. Flowers. (*Illustrated*)... 213

MEETING AT DENVER, FEBRUARY 19, 1916.

The Future of Water Power in the United States—By Charles W. Comstock... 249

MEETING AT SCHENECTADY, MARCH 7, 1916.

Iron Losses in Direct-Current Machines—By B. G. Lamme. (*Illustrated*)... 261

MEETING AT NEW YORK, MARCH 10, 1916.

The Influence of Frequency of Alternating or Infrequently Reversed Current on Electrolytic Corrosion—By Burton McCollum and G. H. Ahlborn. (*Illustrated*)... 301

MEETING AT NEW YORK, APRIL 14, 1916.

High-Voltage D-C. Railway Practise—By Clarence Renshaw... 347

MEETING AT WASHINGTON, APRIL 26, 1916.

Electrochemical Industries and Their Interest in the Development of Water Powers—By Lawrence Addicks... 385
Water Power Development and the Food Problem—By Allerton S. Cushman... 393
Relation of Water Power to Transportation—By Lewis B. Stillwell... 403
Water Power and Defense—By W. R. Whitney... 431
The Water Power Situation, Including Its Financial Aspect—By Gano Dunn... 441

MEETING AT CLEVELAND, JUNE 27 TO 30, 1916.

The Relation of Pure Science to Industrial Research—President's Address—By J. J. Carty....... 479
Standardization—By C. le Maistre....... 489
Electric Drive for Reversing Rolling Mills—By Wilfred Sykes and David Hall. (*Illustrated*)....... 501
Motor Equipments for the Recovery of Petroleum—By W. G. Taylor. (*Illustrated*)....... 539
Report of the Transmission Committee—By Percy H. Thomas, Chairman. (*Illustrated*)....... 555
Effect of Barometric Pressure on Temperature Rise of Self-Cooled Stationary Induction Apparatus—By V. M. Montsinger. (*Illustrated*)....... 599
The Restoration of Service After a Necessary Interruption—By F. E. Ricketts. (*Illustrated*)....... 635
Studies in Lightning Protection on 4000-Volt Circuits—By D. W. Roper. (*Illustrated*)....... 655
Experience and Recent Developments in Central Station Protective Apparatus.—By N. L. Pollard and J. T. Lawson. (*Illustrated*)....... 695
Protection of High-Voltage Distribution Systems by Isolating Transformers—By O. O. Rider....... 717
Megger and Other Tests on Suspension Insulators—By F. L. Hunt 735
Experiences in Testing Porcelain—By E. E. F. Creighton. (*Illustrated*)....... 739
A Method of Grading Suspension Insulators—By R. H. Marvin. (*Illustrated*)....... 745

MEETING AT SCHENECTADY, MAY 4, 1916.

Illumination of the Panama-Pacific International Exposition—By W. D'A. Ryan. (*Illustrated*)....... 757

CONTENTS.

MEETING AT CLEVELAND, JUNE 27 TO 30, 1916.

The Effect of High Continuous Voltages on Air, Oil and Solid Insulations—By F. W. Peek, Jr. (*Illustrated.*) 783

The Corona Voltmeter—By J. B. Whitehead and M. W. Pullen. (*Illustrated.*) 809

Theory of Parallel Grounded Wires and Production of High Frequencies in Transmission Lines—By E. E. F. Creighton. (*Illustrated.*) 845

Suggestions for Electrical Research in Engineering Colleges—By V. Karapetoff 895

Tractive Resistances to a Motor Delivery Wagon on Different Roads and at Different Speeds—By A. E. Kennelly and O. R. Schurig. (*Illustrated.*) 925

Application of a Polar Form of Complex Quantities to the Calculation of Alternating-Current Phenomena—By N. S. Diamant .. 957

MEETING AT SEATTLE, WASH., SEPTEMBER 5 TO 9, 1916.

A Distribution System for Domestic Power Service from Commercial and Engineering Standpoints—By Carl H. Hoge and Edgar R. Perry. (*Illustrated.*) 983

Some Features of Domestic Electric Cooking and Heating—By H. B. Pierce. (*Illustrated.*) 1001

Temperature Rise of Insulated Lead-Covered Cables—By Richard C. Powell. (*Illustrated.*) 1017

Inductive Interference as a Practical Problem—By A. H. Griswold and R. W. Mastick 1051

Testing for Defective Insulators on High Tension Transmission Lines—By B. G. Flaherty 1095

The High-Voltage Potentiometer—By Harris J. Ryan. (*Illustrated.*) 1131

An Artificial Transmission Line with Adjustable Line Constants—By C. Edward Magnusson and S. R. Burbank. (*Illustrated.*). 1137

Characteristics of Admittance Type of Wave Form Standard—By Frederick Bedell. (*Illustrated.*) 1155

Insulator Failures Under Transient Voltages—By W. D. Peaslee. (*Illustrated.*) 1187

MEETING AT CHICAGO, SEPTEMBER 20, 1916.

Underground Distribution Systems—By G. J. Newton 1207

Steel Conductors for Transmission Lines—By H. B. Dwight. (*Illustrated.*) 1237

MEETING AT TORONTO, SEPTEMBER 22, 1916.

Electrical Machinery Tests and Specifications Based on Modern Standards—By H. M. Hobart 1259

MEETING AT PHILADELPHIA, OCTOBER 13, 1916.

The Power Company's Problem in the Electric Supply for Large Single-Phase Load—By William C. L. Eglin 1289
Supply of Single-Phase Loads from Central Stations—By Philip Torchio. (*Illustrated.*) 1293
Single-Phase Power Production—By E. F. W. Alexanderson and G. H. Hill. (*Illustrated.*) 1315
Single-Phase Power Service from Central Stations—By R. E. Gilman and C. Le G. Fortescue. (*Illustrated.*) 1329

MEETING AT NEW YORK, NOVEMBER 10, 1916.

The Effect of Recent Decisions on the Work of Inventory and Appraisal—By Philander Betts 1369
Continuous Inventories; Their Preparation and Value—By Harry E. Carver 1375
Growth and Depreciation—By Julian Loebenstein 1389

MEETING AT SAN FRANCISCO, NOVEMBER 24, 1916.

Ceramics in Relation to the Durability of Porcelain Suspension Insulators—By Harris J. Ryan. (*Illustrated.*) 1437
Experiments on Porcelain Suspension Insulator Units—By J. Cameron Clark. (*Illustrated.*) 1453
Investigation of Suspension Insulator Deterioration—By J. E. Woodbridge 1467

MEETING AT CHICAGO, NOVEMBER 27, 1916.

Temperature Distribution in Electrical Machinery—By B. G. Lamme. (*Illustrated.*) 1471
Rational Temperature Guarantees for Large A-C. Generators—By F. D. Newbury. (*Illustrated.*) 1489

MEETING AT BOSTON, DECEMBER 8, 1916.

Rupturing Capacities of Oil Circuit Breakers—By Stephen Q. Hayes 1523
Rating of Oil Circuit Breakers—By E. M. Hewlett 1531

APPENDIX.

Standardization Rules of the A. I. E. E 1551
Report of the Joint Rubber Insulation Committee—1916 1663
Preliminary Report by the American Committee on Electrolysis 1683
Report of Board of Directors for Fiscal Year Ending April 30, 1916 1835

Index to Papers and Discussions v
Index to Authors vii
Synoptical and Topical Index .... End of Part II

INDEX

Note: For complete topical and synoptical index see end of Part II

PAPERS AND DISCUSSIONS

Chattering Wheel Slip in Electric Motive Power. (Illustrated) (*G. M. Eaton*) 175
Crest Voltmeter, The. (Illustrated) (*L. W. Chubb*) 109
Crest Voltmeters. (Illustrated) (*C. H. Sharp and E. D. Doyle*) 99
Effect of Barometric Pressure on Temperature Rise of Self-Cooled Stationary Induction Apparatus. (*V. M. Montsinger*) 599
Electric Drive for Reversing Rolling Mills. (Illustrated) (*Wilfred Sykes and David Hall*) 501
Electrochemical Industries and Their Interest in the Development of Water Powers. (*Lawrence Addicks*) 385
Experience and Recent Developments in Central Station Protective Features. (Illustrated) (*N. L. Pollard and J. T. Lawson*) 695
Experience in Testing Porcelain. (Illustrated). (*E. E. F. Creighton*) 739
Future of Water Power in the United States, The. (*Charles W. Comstock*) 249
High Voltage D-C. Railway Practise. (*Clarence Renshaw*) 347
Illumination of the Panama-Pacific International Exposition. (Illustrated). (*W. D'A. Ryan*) 757
Influence of Frequency of Alternating or Infrequently Reversed Current on Electrolytic Corrosion, The. (Illustrated). (*Burton McCollum and G. H. Ahlborn*) 301
Iron Losses in Direct-Current Machines. (Illustrated). (*B. G. Lamme*) 261
Liquid Rheostat in Locomotive Service, The. (Illustrated). (*A. J. Hall*) 167
Megger and Other Tests on Suspension Insulators. (*F. L. Hunt*) .. 735
Method of Determining the Correctness of Polyphase Wattmeter Connections, (Illustrated). (*W. B. Kouwenhoven*) 183
Motor Equipments for the Recovery of Petroleum. (Illustrated). (*W. G. Taylor*) 539
Municipally-Operated Electrical Utilities of Western Canada, The. (*A. G. Christie*) 33
New Method of Grading Suspension Insulators, A. (Illustrated). (*R. H. Marvin*) 745
Notes on the Measurement of High Voltage. (Illustrated). (*William R. Work*) 119
Operation of the Norfolk and Western Railway. (Illustrated). (*F. E. Wynne*) 147
Outline of Theory of Impulse Currents. (*Charles P. Steinmetz*) 1
Protection of High-Voltage Distribution Systems by Isolating Transformers. (*O. O. Rider*) 717
Relation of Pure Science to Industrial Research, The. President's Address. (*J. J. Carty*) 479
Relation of Water Power to Transportation. (*Lewis B. Stillwell*) .. 403
Report of the Transmission Committee. (Illustrated) (*Percy H. Thomas, Chairman.*) 555
Restoration of Service After a Necessary Interruption, The. (Illustrated). (*F. E. Ricketts*) 635
Standardization (*C. le Maistre*) 489
Studies in Lightning Protection on 4000-Volt Circuits. (Illustrated) (*D. W. Roper*) 655
True Nature of Speech, The. (Illustrated). (*John B. Flowers*) 213
Voltmeter Coil in Testing Transformers, The. (*A. B. Hendricks*) .. 117
Water Power and Defense. (*W. R. Whitney*) 431
Water Power Development and the Food Problem. (*Allerton S. Cushman*) 393
Water Power Situation, Including Its Financial Aspect, The. (*Gano Dunn*) 441

ol. 35
916

INDEX TO AUTHORS

Adams, Comfort A., Discussion 209, 236, 499
Addicks, Lawrence, Paper 385; Discussion 428, 459
Ahlborn, G. H., Paper 301
Armstrong, A. H., Discussion 154, 371
Arthur, William, Discussion 163
Atwater, C. G., Discussion 465
Baekeland, L. H., Discussion 425, 461
Behrend, B. A., Discussion 160
Betts, Philander, Discussion 88
Bolton, R. P., Discussion 92
Burnham, George A., Discussion 651
Burnham, Joseph L., Discussion 295
Carle, N. A., Discussion 584, 587, 588
Carter, W. A., Discussion 590
Carty, J. J., Paper 479; Discussion 426
Chase, P. H., Discussion 588, 724
Cheney, Edward J., Discussion 95
Christie, A. G., Paper 33; Discussion 97
Chubb, L. W., Paper 109; Discussion 209, 235, 339
Comstock, Charles W., Paper 249
Crehore, Albert C., Discussion 232, 236
Creighton, E. E. F., Paper 739; Discussion 586, 588, 720, 754
Crichton, L. N., Discussion 589, 652
Crosby, Oscar T., Discussion 473
Cushman, Allerton S., Paper 393; Discussion 428
Davis, William J., Jr., Discussion 363
Diamant, N. S., Discussion 731
Dodd, S. T., Discussion 180
Doyle, E. D., Paper 99
Dudley, A. M., Discussion 553
Dunn, Gano, Paper 441; Discussion 423, 459, 476
Eaton, G. M., Paper 175; Discussion 182
Erben, H. F. T., Discussion 287
Finney, John H., Discussion 459
Flowers, John B., Paper 213; Discussion 247
Foster, William J., Discussion 294
Ganz, A. F., Discussion 330
Goodwin, Harold, Jr., Discussion 590, 649
Gray, Alexander, Discussion 534, 631
Haar, Selby, Discussion 374
Hall, A. J., Paper 167
Hall, David, Paper 501
Hammer, William J., Discussion 234
Hayden, J. L. R., Discussion 332
Hellmund, R. E., Discussion 156, 161, 173
Hendricks, A. B., Jr., Paper 117
Hering, Carl, Discussion 335
Hobart, H. M., Discussion 163, 292
Hunt, F. L., Paper 735; Discussion 589, 590
James, H. D., Discussion 527
Jeffries, E. S., Discussion 522
Junkersfeld, Peter, Discussion 584
Kelly, Joseph T., Jr., Discussion 652
Kennelly, A. E., Discussion 30

Kierstead, F. H., Discussion 289
Kintner, S. M., Discussion 333
Knight, C. D., Discussion 172
Kouwenhoven, W. B., Paper 183; Discussion 210
Lamme, B. G., Paper 261; Discussion 298
Langsdorf, A. S., Discussion 297
Lawson, J. T., Paper 695; Discussion 587, 727
le Maistre, C., Paper 489; Discussion 498
Lidbury, F. A., Discussion 420, 457
Liljenroth, F. G., Discussion 527
Lindemann, Peter, Discussion 534
Lippelt, Hans, Discussion 27
Martin, C. B., Discussion 336
Marvin, R. H., Paper 745
Maver, William, Jr., Discussion 233
Maxwell, Alexander, Discussion 329
McCollum, Burton, Paper 301; Discussion 342
Merrill, W. L., Discussion 181
Montignani, J. O., Discussion 729
Montsinger, V. M., Paper 599; Discussion 632
Moody, W. S., Discussion 288
Mouradian, H., Discussion 732
Oesterreicher, S. I., Discussion 369
Osgood, Farley, Discussion 497
Page, H. S., Discussion 533
Pannell, Ernest V., Discussion 370
Pauly, K. A., Discussion 520
Peek, F. W., Jr., Discussion 753
Pender, Harold, Discussion 26
Petty, D. M., Discussion 526
Pollard, N. L., Paper 695; Discussion 734
Potter, Wm. B., Discussion 289, 364
Pratt, W. H., Discussion 207
Price, Bernard, Discussion 590
Pupin, M. I., Discussion 24
Randolph, L. S., Discussion 427
Reid, Arthur, Discussion 96
Renshaw, Clarence, Paper 347; Discussion 379
Ricketts, F. E., Paper 635
Rider, O. O., Paper 717
Roberts, Thomas M., Discussion 339
Robinson, L. T., Discussion 232, 296
Roper, D. W., Paper 655; Discussion 731
Rushmore, David B., Discussion 417, 472, 586, 587, 731
Ryan, W. D'A., Paper 757
Sawin, G. A., Discussion 208
Schuchardt, R. F., Discussion 590, 649, 730
Schwartz, Carl, Discussion 374
Scott, Charles F., Discussion 162, 181
Sharp, C. H., Paper 99; Discussion 96, 497
Shepard, Francis H., Discussion 157
Slichter, W. I., Discussion 160, 180
Smith, George R., Discussion 470
Sorensen, R. W., Discussion 627
Spooner, Thomas, Discussion 340
Sprague, Frank J., Discussion 361
Steinmetz, Charles P., Paper 1; Discussion 21, 30, 497, 722
Stillwell, Lewis B., Paper 403; Discussion 429
Storer, N. W., Discussion 375
Stott, Henry G., Discussion 91, 421
Street, E. T., Discussion 590, 651
Sykes, Wilfred, Paper 501; Discussion 536
Taylor, J. B., Discussion 241, 587, 588, 652, 728

Taylor, W. G., Paper.. 539
Thomas, Percy H., Paper.. 555
Toch, Maxmilian, Discussion.. 342
Torchio, Philip, Discussion.. 328
Townley, Calvert, Discussion..........................367, 466
Troy, M. O., Discussion.. 584
Tschentscher, R., Discussion.. 526
Way, Asa P., Discussion.. 335
Whitehead, J. B., Discussion.. 424
Whitney, W. R., Paper.. 431
Wiley, Brent, Discussion.. 531
Williams, H. B., Discussion.. 232
Wood, Benjamin F., Discussion.. 370
Woodbury, F., Discussion.. 553
Woodrow, H. R., Discussion..........................588, 650
Work, William R., Paper.. 119
Wynne, F. E., Paper 147; Discussion.. 164

INDEX

Note: For complete topical and synoptical index see end of Part II

PAPERS AND DISCUSSIONS

Application of a Polar Form of Complex Quantities to the Calculation of Alternating-Current Phenomena.................... 957
Artificial Transmission Line with Adjustable Line Constants, An, (Illustrated.) (*C. Edward Magnusson and S. R. Burbank*).... 1137
Ceramics in Relation to the Durability of Porcelain Suspension Insulators. (Illustrated.) (*Harris J. Ryan*).............. 1437
Characteristics of Admittance Type of Wave Form Standard. (Illustrated.) (*Frederick Bedell*).......................... 1155
Continuous Inventories; Their Preparation and Value. (*Harry E. Carver*).. 1375
Corona Voltmeter, The. (Illustrated.) (*J. B. Whitehead and M. W. Pullen*).. 809
Distribution System for Domestic Power Service from Commercial and Engineering Standpoints, A. (*Carl H. Hodge and Edgar R. Perry*).. 983
Effect of High Continuous Voltages on Air, Oil and Solid Insulations. (Illustrated). (*F. W. Peek, Jr.*)................... 783
Effect of Recent Decisions on the Work of Inventory and Appraisal, The. (*Philander Betts*)................................ 1369
Electrical Machinery Tests and Specifications Based on Modern Standards. (*H. M. Hobart*)................................ 1259
Experiments on Porcelain Suspension Insulator Units. (Illustrated) (*J. Cameron Clark*).................................. 1453
Growth and Depreciation. (*Julian Loebenstein*)................ 1389
High-Voltage Potentiometer, The. (Illustrated). (*Harris J. Ryan*).. 1131
Inductive Interference as a Practical Problem. (Illustrated). (*A. H. Griswold and R. W. Mastick*)........................ 1051
Insulator Failures under Transient Voltages. (Illustrated.) (*W. D. Peaslee*).. 1187
Investigation of Suspension Insulator Deterioration. (*J. E. Woodbridge*).. 1467
Power Company's Problem in the Electric Supply for Large Single-Phase Load, The, (*William C. L. Eglin*).................. 1289
Preliminary Report by the American Committee on Electrolysis.... 1683
Rating of Oil Circuit Breakers, (E. M. Hewlett)................ 1531
Rational Temperature Guarantees for Large A-C. Generators. (Illustrated). (*F. D. Newbury*)............................ 1489
Report of Board of Directors for Year Ending April 30, 1916....... 1835
Report of the Joint Rubber Insulation Committee............... 1663
Rupturing Capacities of Oil Circuit Breakers. (Stephen Q. Hayes) 1523
Single-Phase Power Production. (Illustrated.) (*E. F. W. Alexanderson and G. H. Hill*).................................. 1315
Single-Phase Power Service from Central Stations. (Illustrated.) (*R. E. Gilman and C. Le G. Fortescue*).................... 1329
Some Features of Domestic Electric Cooking and Heating. (Illustrated). (*H. B. Peirce*)................................ 1001

Standardization Rules 1551
Steel Conductors for Transmission Lines. (Illustrated.) (*H. B. Dwight*) 1237
Suggestions for Electrical Research in Engineering Colleges. (*V. Karapetoff*) 895
Supply of Single-Phase Loads from Central Stations. (Illustrated.) (*Philip Torchio*) 1293
Temperature Distributions in Electrical Machinery. (*B. G. Lamme*) 1471
Temperature Rise of Insulated Lead-Covered Cables. (Illustrated.) (*Richard C. Powell*) 1017
Testing for Defective Insulators on High Tension Transmission Lines. (Illustrated.) (*B. G. Flaherty*) 1095
Theory of Parallel Grounded Wires and Production of High Frequencies in Transmission Lines. (Illustrated.) (*E. E. F. Creighton*) 845
Tractive Resistances to a Motor Delivery Wagon on Different Roads and at Different Speeds. (Illustrated.) (*A. E. Kennelly and O. R. Schurig*) 925
Underground Distribution Systems. (*G. J. Newton*) 1207

INDEX TO AUTHORS

Adams, C. A., Discussion 1358, 1364, 1366, 1541, 1544
Albright, H. C., Discussion 1365
Alexanderson, E. F. W.,Paper 1315; Discussion 1307, 1365
Bauer, W. C., Discussion 1513
Baum, William, Discussion 802
Beck, B. G., Discussion 1230
Bedell, Frederick, Paper 1155; Discussion 1088, 1184
Behrend, B. A., Discussion 1358
Betts, Philander, Paper 1369; Discussion 1418
Boykin, R. M., Discussion 1198
Braymer, B. H., Discussion 921
Buck, H. W., Discussion 997, 1046, 1047, 1048, 1308, 1538, 1541
Burbank, S. R., Paper 1137; Discussion 1152
Burnham, George A., Discussion 1536
Caldwell, F. C., Discussion 915
Carty, J. J., Discussion 920
Carver, Harry E., Paper 1375; Discussion 1421
Cheney, Edward J., Discussion 1416
Cheney, M. E., Discussion 1048
Chrysler, W. L., Discussion 998
Chubb, L. W., Discussion 834, 891, 1177, 1544
Clark, J. Cameron, Paper 1453
Coey, S. C., Discussion 1225, 1228, 1256
Collins, C. R., Discussion 993, 999, 1045, 1047
Colpitts, E. H., Discussion 980
Conrad, N. J., Discussion 1513
Corbett, L. J., Discussion 1090, 1150, 1181
Craighead, James R., Discussion 835
Crawford, M. T., Discussion 992, 1043, 1113
Creighton, E. E. F., Paper 845; Discussion 892, 916, 979, 980, 1123, 1202
Curtis, L. F., Discussion 1013, 1177
Dawes, Chester L., Discussion 804
Del Mar, W. A., Discussion 1048
Diamant, N. S., Paper 957; Discussion 889, 920, 980
Doane, Robert E., Discussion 1251
Doherty, R. E., Discussion 1348, 1364
Dwight, H. B., Paper 1237; Discussion 1257
Egan, F. D., Discussion 1224
Eglin William C. L., Paper 1289; Discussion 1310, 1356, 1364
Ewing, D. D., Discussion 918
Farwell, Stanley, Discussion 803
Fechheimer, C. J., Discussion 1506
Fisken, J. B., Discussion 991, 998, 1012, 1045, 1046, 1048, 1089, 1091, 1182, 1195, 1198
Flaherty, B. G., Paper 1095; Discussion 1117
Flower, M. M., Discussion 1515
Flowers, Alan E., Discussion 912
Fortescue, C. Le G., Paper 1329; Discussion 1366
Foster, W. J., Discussion 1504
Franklin, William S., Discussion 1418
Gear, H. B., Discussion 1228, 1234
Gill, Frank, Discussion 1426

Gille, H. J., Discussion 999, 1015
Gilman, R. E., Paper 1329; Discussion 1355, 1368
Gilson, Barney W., Discussion 1231
Gray, Alexander, Discussion 922, 979, 1503
Griswold, A. H., Paper 1051
Harding, C. Francis, Discussion 836, 919, 1313
Harding, George, Discussion 1115
Harper, John L., Discussion 1307, 1308, 1538
Hayes, Stephen Q., Paper 1523; Discussion 1542, 1545
Henderson, D. F., Discussion 991
Hewlett, E. M., Paper 1531; Discussion 1541, 1548
Hill, G. H., Paper 1315; Discussion 1360
Hobart, H. M., Paper 1259
Hoge, Carl H., Paper 983
Holland, H. F., Discussion 1014
Hommel, Ludwig, Discussion 1231
Hovey, Alfred F., Discussion 1223, 1232
Howes, Robert, Discussion 1000, 1047, 1195
Imlay, L. E., Discussion 1306, 1541
Jackson, W. B., Discussion 1408
Joint Committee on Inductive Interference, Discussion 1171
Jollyman, J. P., Discussion 1118
Junkersfeld, Peter, Discussion 1305, 1365, 1509
Karapetoff, V., Paper 895
Keller, C. A., Discussion 1514
Kennedy, S. M., Discussion 997
Kennelly, A. E., Paper 925
Kershner, J. E., Discussion 1309
King, J. R., Discussion 998
Kunz, Jacob, Discussion 838
Lamme, B. G., Paper 1471; Discussion 1515
Lichtenberg, Chester, Discussion 1534
Lincoln, P. M., Discussion 1510, 1543
Lindemann, P., Discussion 1549
Lindsay, S. C., Discussion 1045, 1046, 1047, 1118
Loebenstein, Julian, Paper 1389; Discussion 1436
Loew, E. A., Discussion 1111
Magnusson, C. Edward, Paper 1137; Discussion 1012, 1113, 1152, 1177
Martindale, E. H., Discussion 1307
Mastick, R. W., Paper 1051; Discussion 1092, 1183, 1198
McCann, W. R., Discussion 1421
Menk, C. A., Discussion 1228
Merriell, F. C., Discussion 1433
Merwin, L. T., Discussion
996, 1043, 1047, 1088, 1092, 1110, 1179, 1184, 1197
Miller, A. A., Discussion 1199
Mini, Jr., J., Discussion 1118
Montsinger, V. M., Discussion 1507
Murray, W. S., Discussion 1303
Nash, L. R., Discussion 1427
Newbury, F. D., Paper 1489; Discussion 1520
Newton, G. J., Paper 1207
Nims, A. A., Discussion 921, 954
Osborne, C. P., Discussion 1115, 1116, 1117
Osborne, Harold S., Discussion 889, 1173
Osgood, Farley, Discussion 1313
Peaslee, W. D., Paper 1187; Discussion
993, 1013, 1089, 1114, 1151, 1182, 1195, 1199, 1205
Peek, F. W., Jr., Paper 783; Discussion 807, 808, 838, 839
Peirce, H. B., Paper 1001
Perry, Edgar R., Paper 983; Discussion
991, 992, 993, 995, 996, 997, 1014
Pollard, N. L., Discussion 1536

Pope, R. W., Discussion........................1013, 1115, 1117
Powell, Richard C., Paper........................1017
Pullen, M. W., Paper........................809
Randall, K. C., Discussion........................1540
Reist, H. G., Discussion........................1349, 1364
Robinson, E. G., Discussion........................996
Robinson, L. T., Discussion........................808
Robinson, R. F., Discussion........................1090
Roper, D. W., Discussion........................1359
Ross, J. D., Discussion........................1151
Rushmore, David B., Discussion..............1255, 1256, 1306, 1416
Ryan, Harris J., Paper 1131, 1437; Discussion..............1110, 1113, 1116, 1183, 1197, 1199
Schurig, O. R., Paper 925; Discussion........................954
Scott, C. F., Discussion........................1309, 1365
Sharp, Clayton H., Discussion........................806, 835
Skinner, C. E., Discussion........................803, 914
Snyder, W. T., Discussion........................1256
Storer, N. W., Discussion........................1307, 1312
Street, George T., Discussion........................1232
Summerhayes, H. R., Discussion..............1306, 1350, 1542, 1546
Taylor, John B., Discussion..............806, 839, 890, 1112, 1538
Torchio, Philip, Paper 1293; Discussion........1311, 1362, 1365, 1366
Tynes, T. E., Discussion..............1223, 1227, 1228, 1234
Wallau, H. L., Discussion........................1350
Weber, F. D., Discussion........................993, 994
Whipple, C. A., Discussion........................1091, 1152
Whitehead, J. B., Paper 809; Discussion..801, 839, 891, 911, 979, 981
Whittemore, G. W., Discussion........................1409
Woodbridge, J. E., Paper........................1467
Woodhull, Fred H., Discussion........................1232
Worcester, T. H., Discussion........................1254

SYNOPTICAL AND TOPICAL

INDEX

OF

A. I. E. E. TRANSACTIONS

Vol. XXXV, Parts I and II

ol. 35
916

The main headings under which these synopses are classified were arrived at by a careful study of all the papers contributed since the organization of the Institute.

The method of making this classification may be called the automatic method, since it is created by sorting the papers themselves into groups and then naming the groups.

Many papers fall naturally into several different groups and in such cases they are inserted under as many different heads as it is thought they rightfully belong.

The classified synopses are designed for those searching for comprehensive information on any given topic, while the subject index is intended for those looking up specific and definite data or information.

MAIN SECTIONS OF SYNOPTICAL INDEX

Page

1. Education 3
2. General Theory 3
3. Units, Measurements and Instruments 4
4. Insulation and Dielectric Phenomena 9
5. Electric Conductors 12
6. Magnetic Properties and Testing of Iron 13
7. Batteries ....
8. Transformers 14
9. Electrical Machinery and Apparatus 14
10. Prime Movers and Steam Boilers ....
11. Power Plants and Central Stations 17
12. Parallel Operation 18
13. Transmission Lines 19
14. Electric Service Disturbances and Protection 21
15. Distribution Systems 26
16. Control, Regulation and Switching 29
17. Traction 31
18. Lighting and Lamps 32
19. Electricity in the Army and Navy ....
20. Miscellaneous Applications of Electricity 32
21. Telephony and Telegraphy 33
22. Miscellaneous Topics and Institute Affairs 34

ol. 35
916

1. EDUCATION

THE RELATION OF PURE SCIENCE TO INDUSTRIAL RESEARCH

President's Address

J. J. Carty **Vol. xxxv—1916, pp. 479-486**

SUGGESTIONS FOR ELECTRICAL RESEARCH IN ENGINEERING COLLEGES

V. Karapetoff **Vol. xxxv—1916, pp. 895-910**

This paper gives a list of topics in electrical engineering suitable for thesis, research and advanced study. A plea is made for systematic research, each college specializing year after year in only a few topics. Cooperation is urged with individual inventors and investigators. Various types of investigation are enumerated, such as invention, experimental study, theoretical study, library search, and compilation of data.

Discussion, pages 911-923, by Messrs. J. B. Whitehead, A. E. Flowers, C. E. Skinner, F. C. Caldwell, E. E. Creighton, D. D. Ewing, C. F. Harding, N. S. Diamant, J. J. Carty, D. H. Braymer, A. A. Nims and A. Gray.

A general discussion from the viewpoints of the college professor, inventor and manufacturer.

2. GENERAL THEORY

OUTLINE OF THEORY OF IMPULSE CURRENTS

C. P. Steinmetz **Vol. xxxv—1916, pp. 1-20**

In Part I it is shown how, from the integral of the general differential equation of the electric circuit, which has been discussed in a previous paper, all types of electric currents are derived as special cases, corresponding to particular values of the integration constants.

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Discussion, pages 20-31, by Messrs. C. P. Steinmetz, M. I. Pupin, H. Pender, H. Lippelt and A. E. Kennelly.

A discussion of the advantages of the synthetic and analytic methods of studying engineering phenomena. A development of the special case under impulse currents of the circuit having capacity in series.

APPLICATION OF A POLAR FORM OF COMPLEX QUANTITIES TO THE CALCULATION OF ALTERNATING-CURRENT PHENOMENA

N. S. Diamant **Vol. xxxv—1916, pp. 957-978**

In the calculation of a-c. phenomena by means of complex quantities, as a rule, the rectangular components of the vector are used. A simple method for dealing directly with the vectors themselves is described and consists in introducing the operator j^n, where n, contrary to ordinary usage, may be any positive or negative fraction. For convenience of reference a summary of formulas is given and also a very short bibliography.

Discussion, pages 979-981, by Messrs. A. Gray, E. E. F. Creighton, J. B. Whitehead, E. H. Colpitts and N. S. Diamant.

A general discussion of the various mathematical determinations.

3. UNITS, MEASUREMENTS AND INSTRUMENTS

CREST VOLTMETERS

C. H. Sharp and E. D. Doyle **Vol. xxxv—1916, p. 99-107**

The paper shows how a voltmeter which will read directly the maximum or crest values obtained in high-voltage testing may be constituted by a combination of an electrostatic voltmeter and an electric valve. Diagrams of connection are shown and results of test given to indicate the validity of the method.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage".

THE VOLTMETER COIL IN TESTING TRANSFORMERS

A. B. Hendricks, Jr. **Vol. xxxv—1916, p. 117**

The advantages of the voltmeter coil in the determination of the high-tension voltage in testing transformers.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage".

THE CREST VOLTMETER

L. W. Chubb **Vol. xxxv—1916, pp. 109-116**

This paper mentions and compares some of the methods of high-voltage measurement and describes in more detail the crest voltmeter with its construction, operation, accuracy and application. The summary states that spark gaps should be only a calibrating standard and a more practical instrument, such as described, the preferred working standard.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage".

NOTES ON THE MEASUREMENT OF HIGH VOLTAGE

W. R. Work **Vol. xxxv—1916, pp. 119-126**

A brief account of some of the experiments made to determine the relative accuracy of certain methods used in measuring high voltage. The methods comprise the use of a tertiary (or voltmeter) coil in the high-tension transformer, the crest voltmeter and the derivation of the high-tension pressure from the primary voltage.

Discussion (including that of papers by Sharp and Doyle, L. W. Chubb and A. B. Hendricks), pages 127-146, by Messrs. E. E. Creighton, F. W. Peek, Jr., F. M. Farmer, F. Bedell, C. A. Adams, W. I. Middleton, J. R. Craighead, C. L. Dawes, J. B. Whitehead, L. W. Chubb, C. H. Sharp, C. F. Harding, W. D. Peaslee, M. G. Newman and A. B. Hendricks, Jr.

A general discussion with particular reference to the oscillograph and visual corona methods of measuring crest voltage.

A METHOD OF DETERMINING THE CORRECTNESS OF POLYPHASE WATT-METER CONNECTIONS

W. B. Kouwenhoven **Vol. xxxv—1916, pp. 183-206**

A description of a method of checking the correctness of the connections of a polyphase watt-hour meter and proof that the methods most commonly used are unreliable. Rules are worked out that make the rectification of incorrect connections simple. Another method is described which may be used on balanced or unbalanced three-phase circuits at any power factor, providing the opening of one phase at a time is permissible.

Discussion, pages 207-211, by Messrs. W. H. Pratt, G. A. Sawin, L. W. Chubb, C. A. Adams and W. B. Kouwenhoven.

A general discussion.

IRON LOSSES IN DIRECT-CURRENT MACHINES

B. G. Lamme **Vol. xxxv—1916, pp. 261-286**

It is shown that no great accuracy is practicable in the calculation of actual iron losses, except in special cases. A brief explanation of several causes of variation in losses is given.

The four principal sources of core loss are considered, namely—armature-ring loss, armature-tooth loss, eddy currents in buried conductors, and pole-face losses. Under eddy current losses an explanation is given of certain losses not usually taken into account with a crude method of calculation and some tabulated results.

Under pole-face losses an empirical formula is given, also tabulated results.

The effect of load on losses is discussed and some of the effects of flux distortion on losses are shown.

Discussion, pages 287-299, by Messrs. H. F. T. Erben, W. S. Moody, W. B. Potter, F. H. Kierstead, H. M. Hobart, W. J. Foster, J. L. Burnham, L. T. Robinson, A. S. Langsdorf and B. G. Lamme.

A general discussion of iron losses in d-c. machines and transformers.

STANDARDIZATION

C. Le Maistre **Vol. xxxv—1916, pp. 489-496**

A general review of development of standardization committees and organizations here and abroad. A citation of the many advantages of proper standardization and an appeal for universal cooperation. Particular reference is given to standardization of electrical machinery with emphasis laid on the adoption of a standard temperature rise basis.

Discussion, pages 497-500, by Messrs. C. H. Sharp, F. Osgood, C. P. Steinmetz, C. Le Maistre and C. A. Adams.

A general discussion.

REPORT OF THE TRANSMISSION COMMITTEE

Percy H. Thomas, Chairman **Vol. xxxv—1916, pp. 555-583**

I. Data from Operating Plants on the Effect of Altitude on the Operating Temperature Rise of Electrical Apparatus.

II. Experience with Grounded Neutral on High-Tension Transmission Lines.

Discussion, pages 584-597, by Messrs. N. A. Carle, M. O. Troy, P. Junkersfeld, E. E. F. Creighton, D. B. Rushmore, J. T. Lawson, J. B. Taylor, P. H. Chase, H. R. Woodrow, E. C. Stone, F. L. Hunt, L. N. Crichton, R. F. Schuchardt, E. T. Street, H. Goodwin, Jr., W. A. Carter and B. Price.

A general discussion of experience with systems, grounded and ungrounded. Very complete description of the Victoria Falls and Transvaal Power Company, Ltd., and the Rand Mines Power Supply Co., Ltd.

EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED STATIONARY INDUCTION APPARATUS

V. M. Montsinger **Vol. xxxv-1916, pp. 599-626**

This paper is divided into three parts, as follows; (1) A general review of the principal laws of the dissipation of heat,—radiation, conduction and convection. (2) The development of a simple formula for the effect of altitude on the cooling of surfaces of different shapes. (3) A general discussion of the method of conducting experimental observations at different altitudes on three different shaped surfaces.

Discussion, pages 627-633, by Messrs. R. W. Sorensen, A. Gray and V. M. Montsinger.

A general discussion of methods and results obtained.

MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS

F. L. Hunt **Vol. xxxv—1916, pp. 735-738**

This paper gives the results of megger tests made on disk insulators on a 66,000-volt transmission line in Massachusetts after 2.5 years operation. The percentage of failures in different positions in the string is given on both strain and suspension towers. The actual cost of making these tests under different conditions of weather and of service requirements is given per insulator on the line, per bad insulator and per tower.

Discussion incorporated with that of paper by R. H. Marvin on "A New Method of Grading Suspension Insulators".

EXPERIENCES IN TESTING PORCELAIN

E. E. F. Creighton **Vol. xxxv—1916, pp. 739-744**

The results of numerous experiences in testing porcelain insulators particularly in regard to porosity, absorption of water, surface leakage and dielectric losses. Considerable energy is required to drive moisture out of a porous insulator and it has been found best to restrict the oscillator testing to dry porcelain, whereas the wetter the porcelain the more effective is the 60-cycle test.

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R. H. Marvin **Vol. xxxv—1916, pp. 745-752**

Attention is drawn to the known disadvantages of the uneven distribution of voltage in long strings of disks. The general theory showing how the distribution is determined by the various capacities of the units is given. It is shown how the distribution can be improved by grading, or varying the internal capacity of the units.

The proposed method of grading consists in placing flat metal rings on the insulator, around cap and stud respectively, the porcelain disk being enlarged for this purpose.

A simple method of measuring the voltage distribution is described using a single needle gap.

The results of tests with and without grading are given, the graded strings showing a decidedly better distribution of voltage.

Discussion, pages 753-755, by Messrs. F. W. Peek, Jr., and E. E. F. Creighton.

A general discussion.

THE CORONA VOLTMETER

J. B. Whitehead and M. W. Pullen **Vol. xxxv—1916, pp. 809-833**

An instrument is described in which the first appearance of corona is used as a measure of the applied voltage. The electroscope, the galvanometer or the telephone are used to determine the first appearance of corona. Tests showing the constancy and permanence of the instrument are described.

Discussion, pages 834-843, by Messrs. L. W. Chubb, C. H. Sharp, J. R. Craighead, C. F. Harding, F. W. Peek, Jr., J. Kunz, J. B. Taylor and J. B. Whitehead.

Arguments for and against the corona voltmeter as compared with other methods of measuring high voltages.

TEMPERATURE RISE OF INSULATED LEAD-COVERED CABLES

Richard C. Powell **Vol. xxxv—1916, pp. 1017-1042**

After a brief historical note, the factors that determine the rate of temperature rise of a cable are considered. The thermal conductivity is expressed in terms of volume thermal conductivity of the insulation, the surface thermal conductivity of the lead sheath, and the dimensions of the cable. A formula is given for calculating increased temperature due to stray currents in the lead sheath. Carrying capacity is also considered from the viewpoint of the thermal properties of the duct line. The overload or intermittent rating is calculated from a given formula. Variable air temperature is discussed. Various formulas given are developed in three appendixes.

Discussion, pages 1043-1050, by Messrs. M. T. Crawford, L. T. Merwin, J. B. Fisken, S. C. Lindsay, C. R. Collins, H. W. Buck, R. Howes, M. E. Cheney and W. A. Del Mar.

A general discussion with special emphasis on the effect on temperature rise of adjacent power lines and crossovers. Experiences of several large power companies.

TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES

B. G. Flaherty **Vol. xxxv—1916, pp. 1095-1109**

A discussion of the importance and necessity of field tests on high-tension insulators and three methods of making such tests, viz; with the oscillator, the megger, and the telephone receiver. The latter is described in detail and some data given on its development and use on a 60,000-volt-line. Laboratory checks on defective insulators are given. Figures of cost for locating and replacing defective units are given. A method of studying rate of depreciation is outlined.

Discussion, pages 1110-1129, by Messrs. H. J. Ryan, L. T. Merwin, E. A. Loew, J. B. Taylor, C. E. Magnusson, M. T. Crawford, W. D. Peaslee, R. W. Pope, C. P. Osborne, G. Harding, B. G. Flaherty, S. C. Lindsay, J. P. Jollyman, J. Mini, Jr., and E. E. Creighton.

Advantages and disadvantages of various methods of detecting and testing faulty insulators, question of removal, oil impregnation of porous insulators, value of grounded neutral, etc.

THE HIGH-VOLTAGE POTENTIOMETER

Harris J. Ryan **Vol. xxxv—1916, pp. 1131-1136**

Description of a high-voltage potentiometer which may be made at reasonable expense consisting of a water resistance potential distributor and a sparking probe potential difference detector. The results of an integrity trial are charted. The device is intended for investigations in which the results are not required to be known within 2 or 3 per cent of their actual value.

No discussion.

AN ARTIFICIAL TRANSMISSION LINE WITH ADJUSTABLE LINE CONSTANTS

C. Edward Magnusson and S. R. Burbank **Vol. xxxv—1916, pp. 1137-1149**

A description of an artificial transmission line which can be readily adjusted to represent 200 miles (321.86 km.) of commercial transmission lines of any spacing up to a maximum of 120 in. (3 m.) and of any size wire up to 4/0 copper. It can also be made to correspond to aerial or cable telephone lines and to power cables. The use of this line is illustrated by a number of typical experiments.

Discussion, pages 1150-1153, by Messrs. L. J. Corbett, W. D. Peaslee, J. D. Ross, S. R. Burbank, C. A. Whipple and C. E. Magnusson.

A general discussion of the value of artificial transmission lines.

CHARACTERISTICS OF ADMITTANCE TYPE OF WAVE-FORM STANDARD

Frederick Bedell **Vol. xxxv—1916, pp. 1155-1170**

A description of the characteristics of a certain type of standard for determining how near an actual wave is to a true sine wave and for prescribing allowable limits of deviation. An investigation to determine whether a standard can be specified that will be more suitable in its characteristics and more practical in its application.

Discussion, pages 1171-1186, by Messrs. H. S. Osborne, L. F. Curtis, C. E. Magnusson, L. W. Chubb, L. T. Merwin, L. J. Corbett, J. B. Fisken, W. D. Peaslee, H. J. Ryan, R. W. Mastick, F. Bedell and Report by Joint Committee on Inductive Interference.

A discussion of the various factors involved in the selection of a wave-shape standard and the penalizing of upper harmonics. An appeal for cooperation between power companies, telephone companies and manufacturers.

EXPERIMENTS ON PORCELAIN SUSPENSION INSULATOR UNITS

J. Cameron Clark **Vol. xxxv-1916, pp. 1453-1466**

A very complete description of experiments on porcelain suspension insulator units. Preliminary organization, scope of tests, unusual equipment required to measure very high resistance of sound dry insulators. Results tabulated when insulators were subjected to mechanical stress, voltages of 1,000 to 30,000, to temperature variation, also effect of moisture. Description of attempted methods of water-logging insulators.

No discussion.

TEMPERATURE DISTRIBUTIONS IN ELECTRICAL MACHINERY

B. G. Lamme **Vol. xxxv—1916, pp. 1471-1488**

The fundamental principles governing heat distribution and temperature in electrical apparatus. Heat generation, heat flow and heat dissipation and resultant temperature are discussed. Paths of heat flow and effects of heat resistance of such paths discussed. The effects of rapid head flow on equalization of temperatures and on their measurement. Fallacies in temperature guarantees and indications pointed out. Some of more common errors in methods of measurement described.

Discussion incorporated with that of paper by F. D. Newbury on "Rational Temperature Guarantees for Large A-C. Generators.

RATIONAL TEMPERATURE GUARANTEES FOR LARGE A.C. GENERATORS

F. D. Newbury **Vol. xxxv—1916, pp. 1489-1502**

An argument for the standardization of temperature guarantees when based on internal temperatures as measured by thermocouples. It is recommended that in all cases the maximum safe operating temperature of the insulation be used as temperature guarantee instead of a lower temperature. Arguments are presented from the stand-point of both operating and designing engineers. Curves are shown illustrating temperature conditions in stator and rotor of a large high-voltage turbogenerator. Examples are given showing that a low temperature rise guarantee for the stator does not necessarily result in overload margin. To be certain of overload margin specifications must call for maximum rating desired.

Discussion, pages 1503-1522, by Messrs. A. Gray, W. J. Foster, C. J. Fechheimer, V. M. Montsinger, P. Junkersfeld, P. M. Lincoln, W. C. Bauer, N. J. Conrad, C. A. Keller, M. M. Flower, B. G. Lamme, and F. D. Newbury.

A general discussion.

4. INSULATION AND DIELECTRIC PHENOMENA

STUDIES IN LIGHTNING PROTECTION ON 4000-VOLT CIRCUITS

D. W. Roper **Vol. xxxv—1916, pp. 655-694**

Investigations over a five-year period on a distributing system covering about 180 square miles of the city of Chicago, supplying about 250,000 customers through about 16,000 transformers. A number of theories were tried out in practise and results are given in detail. The conditions during the year 1915 and records obtained from lightning storms during the year are set forth by means of maps, drawings and tables. An analysis of results is followed by a list of conclusions.

Discussion incorporated with that of paper by O. O. Rider on "Protection of High-Voltage Distribution Systems by Isolating Transformers".

MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS

F. L Hunt **Vol. xxxv—1916, pp. 735-738**

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A general discussion.

THE EFFECT OF HIGH CONTINUOUS VOLTAGES ON AIR, OIL AND SOLID INSULATIONS

F. W. Peek, Jr. **Vol. xxxv—1916, pp. 783-800**

This paper gives the results of experiments on the dielectric strength of air, oil and solid insulations determined for d-c. voltages up to 150 kv.

and compared with a-c. results. Visual corona voltage and variation of voltage with air density. Spark-over voltages in air and oil. D-c. breakdown voltages of solid insulations as compared with a-c. High-voltage direct current in cable testing.

Discussion, pages 801-808, by Messrs. J. B. Whitehead, W. Baum, S. Farwell, C. E. Skinner, C. L. Dawes, C. H. Sharp, J. B. Taylor, F. W. Peek, Jr., and L. T. Robinson.

A general discussion with amplification of certain features such as spark-over between concentric cylinders, the Thury high-tension d-c. system, etc.

TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES

B. G. Flaherty **Vol. xxxv—1916, pp. 1095-1109**

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Advantages and disadvantages of various methods of detecting and testing faulty insulators, question of removal, oil impregnation of porous insulators, value of grounded neutral, etc.

ol. 35
916

INSULATOR FAILURES UNDER TRANSIENT VOLTAGES

W. D. Peaslee **Vol. xxxv—1916, pp. 1187-1194**

This paper presents the results of recent investigations on the failure of insulators under impact and combined impact and normal frequency voltages. Microphotographs are included. The breakdown of a dielectric involves energy which is a time function, and the importance of the duration of the stress in determining the magnitude of the voltage necessary to puncture an insulator are discussed. The importance of the elimination of air holes and defects in porcelain is shown. Some essential features of a successful line insulator are stated.

Discussion, pages 1195-1205, by Messrs. J. B. Fisken, W. D. Peaslee, R. Howes, L. T. Merwin, H. J. Ryan, R. W. Mastick, R. M. Boykin, A. A. Miller and E. E. F. Creighton.

A general discussion including experiences of certain power transmission lines.

CERAMICS IN RELATION TO THE DURABILITY OF PORCELAIN SUSPENSION INSULATORS

Harris J. Ryan **Vol. xxxv—1916, pp. 1437—1452**

The fundamental requirements in satisfactory high-voltage line insulators are summarized and particular emphasis is placed upon the need for coordinated study of service durability. The effect of porosity upon durability is explained in detail and an appeal made for the establishment of a practical porosity elimination test.

The manufacture and structure of electrical porcelain is studied from the viewpoint of the ceramist, with many quotations and illustrations taken from the Transactions of the American Ceramic Society.

The author briefly states the conclusions at which he has arrived and gives a very complete list of references and notes.

No discussion.

EXPERIMENTS ON PORCELAIN SUSPENSION INSULATOR UNITS

J. Cameron Clark **Vol. xxxv—1916, pp. 1453-1466**

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No discussion.

INVESTIGATION OF SUSPENSION INSULATOR DETERIORATION

J. E. Woodbridge **Vol. xxxv—1916, pp. 1467-1470**

This paper gives an outline of an investigation of suspension insulator deterioration. It cites the origin of the investigation, the limiting factors encountered and methods employed to overcome them.

No discussion.

5. ELECTRIC CONDUCTORS

OUTLINE OF THEORY OF IMPULSE CURRENTS

C. P. Steinmetz **Vol. xxxv—1916, pp. 1-20**

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TEMPERATURE RISE OF INSULATED LEAD-COVERED CABLES

Richard C. Powell **Vol. xxxv—1916, pp. 1017-1042**

After a brief historical note, the factors that determine the rate of temperature rise of a cable are considered. The thermal conductivity is expressed in terms of volume thermal conductivity of the insulation, the surface thermal conductivity of the lead sheath, and the dimensions of the cable. A formula is given for calculating increased temperature due to stray currents in the lead sheath. Carrying capacity is also considered from the viewpoint of the thermal properties of the duct line. The overload or intermittent rating is calculated from a given formula. Variable air temperature is discussed. Various formulas given are developed in three appendixes.

Discussion, pages 1043-1050, by Messrs. M. T. Crawford, L. T. Merwin, J. B. Fisken, S. C. Lindsay, C. R. Collins, H. W. Buck, R. Howes, M. E. Cheney and W. A. Del Mar.

A general discussion with special emphasis on the effect on temperature rise of adjacent power lines and crossovers. Experiences of several large power companies.

STEEL CONDUCTORS FOR TRANSMISSION LINES

H. B. Dwight **Vol. xxxv—1916, pp. 1237-1250**

This paper states that steel cables will not generally be economical on main transmission lines, except for long spans, and for high altitudes where corona is excessive. They may be advisable as bare conductors for d-c. railway feeders. They deteriorate more rapidly than copper conductors and have very low scrap value. Steel cables for alternating current should be finely stranded and different groups of wire should be spiraled in opposite directions. Medium grades of steel give better results with alternating currents than high priced grades. There is an opening for the profitable use of steel cables on branch lines of power systems of all voltages.

Discussion, pages 1251-1258, by Messrs. R. E. Doane, T. H. Worcester, D. B. Rushmore, S. C. Coey, W. T. Snyder and H. B. Dwight.

A general discussion.

6. MAGNETIC PROPERTIES AND TESTING OF IRON

IRON LOSSES IN DIRECT-CURRENT MACHINES

B. G. Lamme **Vol. xxxv—1916, pp. 261-286**

It is shown that no great accuracy is practicable in the calculation of actual iron losses, except in special cases. A brief explanation of several causes of variation in losses is given.

The four principal sources of core loss are considered, namely—armature-ring loss, armature-tooth loss, eddy currents in buried conductors, and pole-face losses. Under eddy current losses an explanation is given of certain losses not usually taken into account, with a crude method of calculation and some tabulated results.

Under pole-face losses an empirical formula is given, also tabulated results.

The effect of load on losses is discussed and some of the effects of flux distortion on losses are shown.

Discussion, pages 287-299, by Messrs. H. F. T. Erben, W. S. Moody, W. B. Potter, F. H. Kierstead, H. M. Hobart, W. J. Foster, J. L. Burnham, L. T. Robinson, A. S. Langsdorf and B. G. Lamme.

A general discussion of iron losses in d-c. machines and transformers.

8. TRANSFORMERS

THE VOLTMETER COIL IN TESTING TRANSFORMERS

A. B. Hendricks, Jr. **Vol. xxxv—1916, p. 117**

The advantages of the voltmeter coil in the determination of the high-tension voltage in testing transformers.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage."

EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED STATIONARY INDUCTION APPARATUS

V. M. Montsinger **Vol. xxxv—1916, pp. 599-626**

This paper is divided into three parts, as follows: (1) A general review of the principal laws of the dissipation of heat, radiation, conduction and convection. (2) The development of a simple formula for the effect of altitude on the cooling of surfaces of different shapes. (3) A general discussion of the method of conducting experimental observations at different altitudes on three different shaped surfaces.

Discussion, pages 627-633, by Messrs. R. W. Sorensen, A. Gray and V. M. Montsinger.

A general discussion of methods and results obtained.

PROTECTION OF HIGH-VOLTAGE DISTRIBUTION SYSTEMS BY ISOLATING TRANSFORMERS

O. O. Rider **Vol. xxxv—1916, pp. 717-719**

This paper calls attention to the practicability of localizing line disturbances by means of transformers. Application is made to high-voltage distribution systems serving the rural communities which results in an interconnected net work of overhead lines.

Discussion, pages 720-734, by Messrs. E. E. F. Creighton, C. P. Steinmetz, P. H. Chase, J. T. Lawson, J. B. Taylor, J. O. Montignani, R. F. Schuchardt, P. Junkersfeld, D. B. Rushmore, D. W. Roper, N. S. Diamant, H. Mouradian and N. L. Pollard.

A general discussion with particular reference to the split-conductor principle and its relation to ideal relay protection.

9. ELECTRICAL MACHINERY AND APPARATUS

THE LIQUID RHEOSTAT IN LOCOMOTIVE SERVICE

A. J. Hall **Vol. xxxv—1916, pp. 167-171**

A description of the liquid rheostat in locomotive service giving in detail the arrangement of the mechanical parts and means of controlling it.

Discussion, pages 172-173, by Messrs. C. D. Knight and R. E. Hellmund.

A discussion mainly of the liquid rheostat used in mine-hoist service.

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ELECTRIC DRIVE FOR REVERSING ROLLING MILLS

Wilfred Sykes and David Hall **Vol. xxxv—1916, pp. 501-519**

This paper answers some of the questions which have arisen in the rapid displacement of steam drive by electric drive for reversing rolling mills, and describes the constructions which have been found desirable.

Discussion, pages 520-537, by Messrs. K. A. Pauly, E. S. Jeffries, D. M. Petty, R. Tschentscher, H. D. James, F. G. Liljenroth, B. Wiley, H. S. Page, P. Lindemann, A. Gray and W. Sykes.

A discussion of the relative merit of steam and electric drive for reversing mills. Statistics of installation at Steel Company of Canada. Comparison of European and American practise.

MOTOR EQUIPMENTS FOR THE RECOVERY OF PETROLEUM

W. G. Taylor **Vol. xxxv—1916, pp. 539-552**

This paper presents data covering the horse power requirements and kilowatt-hour consumption for the various operations in drilling and maintaining producing oil wells. The use of the slip-ring induction motor for drilling, pumping and cleaning wells. Special controllers and resistance. Pumping, cleaning and "pulling" rods by a Y-delta or two speed machine.

Discussion, pages 553-554, by Messrs. F. Woodbury and A. M. Dudley. General discussion.

EXPERIENCE AND RECENT DEVELOPMENTS IN CENTRAL STATION PROTECTION FEATURES

N. L. Pollard and J. T. Lawson **Vol. xxxv—1916, pp. 695-715**

The protective features described in this paper are some of those now in use on the system of the Public Service Electric Company, which serves a population of about 2,200,000.

The protective devices and schemes discussed are, as follows: Aluminum cell arresters; arcing ground suppressor; faulty cable localizer; cable testing; high-potential and high-frequency testing; generator bus connection scheme; exciter connection scheme; reactors; relays; multi-recorders; insulation resistance recorder; air washers; resistance bulbs and thermocouples; dampers on air-blast transformers; coherer alarm devices; potential indicating devices.

Discussion incorporated with that of paper by O. O. Rider on "Protection of High-Voltage Distribution Systems by Isolating Transformers."

ELECTRICAL MACHINERY TESTS AND SPECIFICATIONS BASED ON MODERN STANDARDS

H. M. Hobart **Vol. xxxv—1916, pp. 1259-1287**

Comparisons are made of the standardization rules for electrical machinery now in force in various countries showing that machinery built in conformance with the American rules will usually also conform with rules employed in other countries. Suggestion is made that 55 degrees could be employed as the ambient temperature of reference for tropical ratings. Attention is called to a series of acceptance tests on some large waterwheel generators and to the temperature results obtained by making cyclic heat runs on these machines.

No discussion.

TEMPERATURE DISTRIBUTIONS IN ELECTRICAL MACHINERY

B. G. Lamme **Vol. xxxv—1916, pp. 1471-1488**

The fundamental principles governing heat distribution and temperature in electrical apparatus. Heat generation, heat flow and heat dissipation and resultant temperature are discussed. Paths of heat flow and effects of heat resistance of such paths discussed. The effects of rapid heat flow on equalization of temperatures and on their measurement. Fallacies in temperature guarantees and indications pointed out. Some of more common errors in methods of measurement described.

Discussion incorporated with that of paper by F. D. Newbury on "Rational Temperature Guarantees for Large A-C. Generators.

RATIONAL TEMPERATURE GUARANTEES FOR LARGE A-C. GENERATORS

F. D. Newbury **Vol. xxxv—1916, pp. 1489-1502**

An argument for the standardization of temperature guarantees when based on internal temperatures as measured by thermocouples. It is recommended that in all cases the maximum safe operating temperature of the insulation be used as temperature guarantee instead of a lower temperature. Arguments are presented from the standpoint of both operating and designing engineers. Curves are shown illustrating temperature conditions in stator and rotor of a large high-voltage turbogenerator. Examples are given showing that a low temperature rise guarantee for the stator does not necessarily result in overload margin. To be certain of overload margin, specifications must call for maximum rating desired.

Discussion, pages 1503-1522, by Messrs. A. Gray, W. J. Foster, C. J. Fechheimer, V. M. Montsinger, P. Junkersfeld, P. M. Lincoln, W. C. Bauer, N. J. Conrad, C. A. Keller, M. M. Flower, B. G. Lamme and F. D. Newbury.

A general discussion.

RUPTURING CAPACITIES OF OIL CIRCUIT BREAKERS

Stephen Q. Hayes **Vol. xxxv—1916, pp. 1523-1530**

A series of notes on the rupturing capacity of oil breakers. Description of result obtained by root-mean-square of maximum peak of current wave that occurs while breaker is opening multiplied by root-mean-square of open-circuit voltage that occurs immediately after breaker opens. Attention called to different classes of ratings. Recommendations made as to most desirable method of rating and ability of breakers to be re-operative.

Discussion incorporated with that of paper by E. M. Hewlett on "Rating of Oil Circuit Breakers".

RATING OF OIL CIRCUIT BREAKERS

E. M. Hewlett **Vol. xxxv—1916, pp. 1531-1533**

Paper points out several difficulties which are encountered in rating of actual circuit breakers, but generally favors that these ratings be on the basis of the current to be opened in the arc at the operating voltage of the system.

Discussion, pages 1534-1549, by Messrs. C. Lichtenberg, N. L. Pollard, G. A. Burnham, J. L. Harper, H. W. Buck, J. B. Taylor, K. C. Randall, L. E. Imlay, C. A. Adams, E. M. Hewlett, S. Q. Hayes, H. R. Summerhayes, P. M. Lincoln, L. W. Chubb and P. Lindemann.

A general discussion.

11. POWER PLANTS AND CENTRAL STATIONS

THE MUNICIPALLY-OPERATED ELECTRICAL UTILITIES OF WESTERN CANADA

A. G. Christie **Vol. xxxv—1916, pp. 33-87**

The paper discusses a number of public utilities in various cities in Western Canada. The characteristics of these cities are reviewed and a brief outline of equipments of the various plants is given. The costs and methods of financing these utilities are discussed at considerable length and the charges for various services are summarized.

Discussion, pages 88-98, by Messrs. P. Betts, H. G. Stott, R. P. Bolton, E. J. Cheney, C. H. Sharp, A. Reid and A. G. Christie.

A general discussion of the advantages and disadvantages of municipal ownership of public utilities and methods of financing them.

THE POWER COMPANY'S PROBLEM IN THE ELECTRIC SUPPLY FOR LARGE SINGLE-PHASE LOAD

W. C. L. Eglin **Vol. xxxv—1916, pp. 1289-1292**

A power company must be able to supply energy of uniform pressure, single-phase, two-phase or three-phase, at whatever voltage best suits customer. These conditions best met by polyphase units. When demand for single-phase current is heavy enough to produce unbalance, some means of balancing must be provided. Three methods are discussed. Correction for power factor on each individual large consumer's line is suggested.

Discussion incorporated with that of paper by Philip Torchio on "Supply of Single-Phase Loads from Central Stations".

SUPPLY OF SINGLE-PHASE LOADS FROM CENTRAL STATIONS

Philip Torchio **Vol. xxxv—1916, pp. 1293-1301**

American central stations have extensively adopted single-phase distribution from polyphase stations. Individual regulators employed.

Generators with good single-phase characteristics or in certain cases generators with kilovolt ampere rating in excess of kilowatt capacity of steam unit are employed. Customers assist balancing by dividing load between phases. Question of power supply to N. Y., N. H. & H. RR. discussed. Equipment described.

Discussion, including that of paper by W. C. L. Eglin, pages 1302-1313, by Messrs. W. S. Murray, P. Junkersfeld, D. B. Rushmore, L. E. Imlay, H. R. Summerhayes, N. W. Storer, E. H. Martindale, E. F. W. Alexanderson, J. L. Harper, H. W. Buck, J. E. Kershner, C. F. Scott, W. C. L. Eglin, P. Torchio, F. Osgood and C. F. Harding.

General discussion.

SINGLE-PHASE POWER PRODUCTION

E. F. W. Alexanderson and G. H. Hill **Vol. xxxv—1916, pp. 1315-1327**

The general tendency of electric power supply is toward centralization of stations and to be consistent stations must be standardized. From this standpoint single-phase power can best be supplied from polyphase systems. Operation and theory of phase converters discussed.

Discussion incorporated with that of paper by Gilman and Fortescue on "Single-Phase Power Service from Central Stations".

SINGLE-PHASE POWER SERVICE FROM CENTRAL STATIONS

R. E. Gilman and C. L. Fortescue **Vol. xxxv—1916, pp. 1329-1347**

An outline of several methods by which single-phase power may be supplied from a polyphase system with advantages and disadvantages. Unbalance in voltage when single-phase power is supplied direct from polyphase circuit explained. Law of distribution of load in polyphase system deduced. Outline of theory of single-phase generator given. Essential requirements for phase balancing, requirements for control apparatus, behavior of balancer under short circuit.

Discussion, (including that of paper by Alexanderson and Hill), pages 1348-1368, by Messrs. R. E. Doherty, H. G. Reist, H. L. Wallau, H. R. Summerhayes, R. E. Gilman, W. C. L. Eglin, B. A. Behrend, C. A. Adams, D. W. Roper, G. H. Hill, P. Torchio, P. Junkersfeld, C. F. Scott, H. C. Albright, E. F. W. Alexanderson, and C. L. Fortescue.

A general discussion of the advantages of various methods of single-phase generation and operation with some facts relative to comparative costs.

12. PARALLEL OPERATION

ELECTRICAL MACHINERY TESTS AND SPECIFICATIONS BASED ON MODERN STANDARDS

H. M. Hobart **Vol. xxxv—1916, pp. 1369-1387**

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No discussion.

13. TRANSMISSION LINES

OUTLINE OF THEORY OF IMPULSE CURRENTS

C. P. Steinmetz **Vol. xxxv—1916, pp. 1-20**

In Part I it is shown how, from the integral of the general differential equation of the electric circuit, which has been discussed in a previous paper, all types of electric currents are derived as special cases, corresponding to particular values of the integration constants.

In Part II an outline of the theory of impulse currents is given. They comprise two classes, the non-periodic and the periodic. The equations of both are given in different form, by exponential and by hyperbolic or trigonometric functions.

A few special cases are discussed.

Discussion, pages 20-31, by Messrs. C. P. Steinmetz, M. I. Pupin, H. Pender, H. Lippelt and A. E. Kennelly.

A discussion of the advantages of the synthetic and analytic methods of studying engineering phenomena. A development of the special cases under impulse currents of the circuit having capacity in series.

REPORT OF THE TRANSMISSION COMMITTEE

Percy H. Thomas, Chairman **Vol. xxxv—1916, pp. 555-583**

I. Data from Operating Plants on the Effect of Altitude on the Operating Temperature Rise of Electrical Apparatus.

II. Experience with Grounded Neutral on High-Tension Transmission Lines.

Discussion, pages 584-597, by Messrs. N. A. Carle, M. O. Troy, P. Junkersfeld, E. E. F. Creighton, D. B. Rushmore, J. T. Lawson, J. B. Taylor, P. H. Chase, H. R. Woodrow, E. C. Stone, F. L. Hunt, L. N. Crichton, R. F. Schuchardt, E. T. Street, H. Goodwin, Jr., W. A. Carter and B. Price.

A general discussion of experience with systems, grounded and ungrounded. Very complete description of the Victoria Falls and Transvaal Power Company, Ltd., and the Rand Mines Power Supply Co., Ltd.

THE RESTORATION OF SERVICE AFTER A NECESSARY INTERRUPTION

F. E. Ricketts **Vol. xxxv—1916, pp. 635-648**

The phenomenal growth during the last few years in the electrical industry has been due as much to the marked advances in the methods of maintaining a uniform service as to any other cause. Attention is called to that class of interruptions which so far have been and will likely continue to be unavoidable and a full description is given of certain means whereby the effect of unavoidable interruptions may be reduced to a minimum.

Discussion, pages 649-654, by Messrs. H. Goodwin, Jr., R. F. Schuchardt, H. R. Woodrow, E. T. Street, G. A. Burnham, J. B. Taylor, L. N. Crichton and J. T. Kelly, Jr.

A general discussion of protective features in use on various systems.

MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS

F. L. Hunt **Vol. xxxv—1916, pp. 735-738**

This paper gives the results of megger tests made on disk insulators on a 66,000-volt transmission line in Massachusetts after 2.5 years operation. The percentage of failures in different positions in the string is given on both strain and suspension towers. The actual cost of making these tests under different conditions of weather and of service requirements is given per insulator on the line, per bad insulator and per tower.

Discussion incorporated with that of paper by R. H. Marvin, on "A New Method of Grading Suspension Insulators".

THEORY OF PARALLEL GROUNDED WIRES AND PRODUCTION OF HIGH FREQUENCIES IN TRANSMISSION LINES

E. E. F. Creighton **Vol. xxxv—1916, pp. 845-888**

An investigation of the value of the overhead grounded wire as used for lightning protection, mechanical support for towers, and a test circuit. The functions of the grounded wire are subdivided into four categories; first, the vertical grounded wire; second, the lightning rod extending above the ground; third, the electrostatic induction in the horizontally situated wires; and fourth, electromagnetic induction. The several factors determining the protective value of a ground wire are fully investigated. Equations expressing the protection of various arrangements of vertical and parallel grounded wires are developed.

Discussion, pages 889-893, by Messrs. H. S. Osborne, N. S. Diamant, J. B. Taylor, J. B. Whitehead, L. W. Chubb and E. E. F. Creighton.

A general discussion.

TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES

B. G. Flaherty **Vol. xxxv-1916, pp. 1095-1109**

A discussion of the importance and necessity of field tests on high-tension insulators and three methods of making such tests, viz; with the oscillator, the megger, and the telephone receiver. The latter is described in detail and some data given on its develpment and use on a 60,000-volt-line. Laboratory checks on defective insulators are given. Figures of cost for locating and replacing defective units are given. A method of studying rate of depreciation is outlined.

Discussion, pages 1110-1129, by Messrs. H. J. Ryan, L. T. Merwin, E. A. Loew, J. B. Taylor, C. E. Magnusson, M. T. Crawford, W. D. Peaslee, R. W. Pope, C. P. Osborne, G. Harding, B. G. Flaherty, S. C. Lindsay, J. P. Jollyman, J. Mini, Jr., and E. E. Creighton.

Advantages and disadvantages of various methods of detecting and testing faulty insulators, question of removal, oil impregnation of porous insulators, value of grounded neutral, etc.

AN ARTIFICIAL TRANSMISSION LINE WITH ADJUSTABLE LINE CONSTANTS

C. Edward Magnusson and S. R. Burbank **Vol. xxxv—1916, pp. 1137-1149**

A description of an artificial transmission line which can be readily adjusted to represent 200 miles (321.86 km.) of commerical transmission lines of any spacing up to a maximum of 120 in. (3 m.) and of any size wire up to 4/0 copper. It can also be made to correspond to aerial or cable telephone lines and to power cables. The use of this line is illustrated by a number of typical experiments.

Discussion, pages 1150-1153, by Messrs. L. J. Corbett, W. D. Peaslee, J. D. Ross, S. R. Burbank, C. A. Whipple and C. E. Magnusson.

A general discussion of the value of artificial transmission lines.

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CREST VOLTMETERS

C. H. Sharp and E. D. Doyle **Vol. xxxv—1916, pp. 99-107**

The paper shows how a voltmeter which will read directly the maximum or crest values obtained in high-voltage testing may be constituted by a combination of an electrostatic voltmeter and an electric valve. Diagrams of connection are shown and results of test given to indicate the validity of the method.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage."

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THE CREST VOLMETER

L. W. Chubb **Vol. xxxv—1916, pp. 109-116**

This paper mentions and compares some of the methods of high-voltage measurement and describes in more detail the crest voltmeter with its construction, operation, accuracy and application. The summary states that spark gaps should be only a calibrating standard and a more practical instrument, such as described, the preferred working standard.

Discussion incorporated with that of paper by W. R. Work on "Notes on the Measurement of High Voltage."

NOTES ON THE MEASUREMENT OF HIGH VOLTAGE

W. R. Work **Vol. xxxv—1916, pp. 119-126**

A brief account of some of the experiments made to determine the relative accuracy of certain methods used in measuring high voltage. The methods comprise the use of a tertiary (or voltmeter) coil in the high-tension transformer, the crest voltmeter and the derivation of the high-tension pressure from the primary voltage.

Discussion (including that of papers by Sharp and Doyle, L. W. Chubb and A. B. Hendricks), pages 127-146, by Messrs. E. E. F. Creighton, F.W. Peek, Jr., F. M. Farmer, F. Bedell, C. A. Adams, W. I. Middleton, J. R. Craighead, C. L. Dawes, J. B. Whitehead, L. W. Chubb, C. H. Sharp, C. F. Harding, W. D. Peaslee, M. G. Newman and A. B. Hendricks, Jr.

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A general discussion of protective features in use on various systems.

STUDIES IN LIGHTNING PROTECTION ON 4000-VOLT CIRCUITS

D. W. Roper **Vol. xxxv—1916, pp. 655-694**

Investigations over a five year period on a distributing system covering about 180 square miles of the city of Chicago, supplying about 250,000 customers through about 16,000 transformers. A number of theories were tried out in practise and results are given in detail. The conditions during the year 1915 and records obtained from lightning storms during the year are set forth by means of maps, drawings and tables. An analysis of results is followed by a list of conclusions.

Discussion, incorporated with that of paper by O. O. Rider on "Protection of High-Voltage Distribution Systems by Isolating Transformers."

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A general discussion with particular reference to the split-conductor principle and its relation to ideal relay protection.

MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS

F. L. Hunt **Vol. xxxv—1916, pp. 735-738**

This paper gives the results of megger tests made on disk insulators on a 66,000-volt transmission line in Massachusetts after 2.5 years operation. The percentage of failures in different positions in the string is given on both strain and suspension towers. The actual cost of making these tests under different conditions of weather and of service requirements is given per insulator on the line, per bad insulator and per tower.

Discussion incorporated with that of paper by R. H. Marvin on "A New Method of Grading Suspension Insulators."

THEORY OF PARALLEL GROUNDED WIRES AND PRODUCTION OF HIGH FREQUENCIES IN TRANSMISSION LINES

E. E. F. Creighton **Vol. xxxv—1916, pp. 845-888**

An investigation of the value of the overhead grounded wire as used for lightning protection, mechanical support for towers, and a test circuit. The functions of the grounded wire are subdivided into four categories; first, the vertical grounded wire; second, the lightning rod extending above the ground; third, the electrostatic induction in the horizontally situated wires; and fourth, electromagnetic induction. The several factors determining the protective value of a ground wire are fully investigated. Equations expressing the protection of various arrangements of vertical and parallel grounded wires are developed.

Discussion, pages 889-893, by Messrs. H. S. Osborne, N. S. Diamant, J. B. Taylor, J. B. Whitehead, L. W. Chubb and E. E. F. Creighton.

A general discussion.

INDUCTIVE INTERFERENCE AS A PRACTICAL PROBLEM

A. H. Griswold and R. W. Mastick **Vol. xxxv—1916, pp. 1051-1087**

A review of the factors which affect inductive interference in telephone circuits from high-voltage power transmission circuits, a presentation of practical considerations regarding the reduction of interference, and description of actual cases of the application of these means of reduction. Balanced and residual voltages and currents, wave shapes of voltages and currents, transposition schemes, three particular cases of parallels.

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A discussion of effects of leaking insulators, charging electrolytic arresters, carelessness in making transpositions and an appeal for cooperation of telephone and power companies.

TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES

B. G. Flaherty **Vol. xxxv—1916, pp. 1095-1109**

A discussion of the importance and necessity of field tests on high-tension insulators and three methods of making such tests, viz; with the oscillator, the megger, and the telephone receiver. The latter is described in detail and some data given on its development and use on a 60,000-volt line. Laboratory checks on defective insulators are given. Figures of cost for locating and replacing defective units are given. A method of studying rate of depreciation is outlined.

Discussion, pages 1110-1129, by Messrs. H. J. Ryan, L. T. Merwin, E. A. Loew, J. B. Taylor, C. E. Magnusson, M. T. Crawford, W. D. Peaslee, R. W. Pope, C. P. Osborne, G. Harding, B. G. Flaherty, S. C. Lindsay, J. P. Jollyman, J. Mini, Jr. and E. E. Creighton.

Advantages and disadvantages of various methods of detecting and testing faulty insulators, question of removal, oil impregnation of porous insulators, value of grounded neutral, etc.

THE HIGH-VOLTAGE POTENTIOMETER

Harris J. Ryan **Vol. xxxv—1916, pp. 1131-1136**

Description of a high-voltage potentiometer which may be made at reasonable expense consisting of a water resistance potential distributor and a sparking probe potential difference detector. The results of an integrity trial are charted. The device is intended for investigations in which the results are not required to be known within 2 or 3 per cent of their actual value.

No discussion.

CHARACTERISTICS OF ADMITTANCE TYPE OF WAVE-FORM STANDARD

Frederick Bedell **Vol. xxxv—1916, pp. 1155-1170**

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A discussion of the various factors involved in the selection of a wave-shape standard and the penalizing of upper harmonics. An appeal for cooperation between power companies, telephone companies and manufacturers.

INSULATOR FAILURES UNDER TRANSIENT VOLTAGES

W. D. Peaslee **Vol. xxxv—1916, pp. 1187-1194**

This paper presents the results of recent investigations on the failure of insulators under impact and combined impact and normal frequency voltages. Microphotographs are included. The breakdown of a dielectric involves energy which is a time function, and the importance of the duration of the stress in determining the magnitude of the voltage necessary to puncture an insulator are discussed. The importance of the elimination of air holes and defects in porcelain is shown. Some essential features of a successful line insulator are stated.

Discussion, pages 1195-1205, by Messrs. J. B. Fisken, W. D. Peaslee, R. Howes, L. T. Merwin, H. J. Ryan, R. W. Mastick, R. M. Boykin, A. A. Miller and E. E. F. Creighton.

A general discussion including experiences of certain power transmission lines.

STEEL CONDUCTORS FOR TRANSMISSION LINES

H. B. Dwight **Vol. xxxv—1916, pp.1237-1250**

This paper states that steel cables will not generally be economical on main transmission lines, except for long spans, and for high altitudes where corona is excessive. They may be advisable as bare conductors for d-c. railway feeders. They deteriorate more rapidly than copper conductors and have very low scrap value. Steel cables for alternating current should be finely stranded and different groups of wire should be spiraled in opposite directions. Medium grades of steel give better results with alternating currents than high priced grades. There is an opening for the profitable use of steel cables on branch lines of power systems of all voltages.

Discussion, pages 1251-1258, by Messrs. R. E. Doane, T. H. Worcester, D. B. Rushmore, S. C. Coey, W. T. Snyder and H. B. Dwight.

A general discussion.

15. DISTRIBUTION SYSTEMS

REPORT OF THE TRANSMISSION COMMITTEE

Percy H. Thomas, Chairman **Vol. xxxv—1916, pp. 555-583**

I. Data from Operating Plants on the Effect of Altitude on the Operating Temperature Rise of Electrical Apparatus.

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Discussion, pages 584-597, by Messrs. N. A. Carle, M. O. Troy, P. Junkerfeld, E. E. F. Creighton, D. B. Rushmore, J. T. Lawson, J. B. Taylor, P. H. Chase, H. R. Woodrow, E. C. Stone, F. L. Hunt, L. N. Crichton, R. F. Schuchardt, E. T. Street, H. Goodwin, Jr., W. A. Carter and B. Price.

A general discussion of experience with systems, grounded and ungrounded. Very complete description of the Victoria Falls andTransvaal Power Company, Ltd., and the Rand Mines Power Supply Co., Ltd.

THE RESTORATION OF SERVICE AFTER A NECESSARY INTERRUPTION

F. E. Ricketts **Vol. xxxv—1916, pp. 635-648**

The phenomenal growth during the last few years in the electrical industry has been due as much to the marked advances in the methods of maintaining a uniform service as to any other cause. Attention is called to that class of interruptions which so far have been and will likely continue to be unavoidable and a full description is given of certain means whereby the effect of unavoidable interruptions may be reduced to a minimum.

Discussion, pages 649-654, by Messrs. H. Goodwin, Jr., R. F. Schuchardt, H. R. Woodrow, E. T. Street, G. A. Burnham, J. B. Taylor, L. N. Crichton and J. T. Kelly, Jr.

A general discussion of protective features in use on various systems.

PROTECTION OF HIGH-VOLTAGE DISTRIBUTION SYSTEMS BY ISOLATING TRANSFORMERS

O. O. Rider **Vol. xxxv—1916, pp. 717-719**

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A DISTRIBUTION SYSTEM FOR DOMESTIC POWER SERVICE FROM COMMERCIAL AND ENGINEERING STANDPOINTS

Carl H. Hoge and Edgar R. Perry **Vol. xxxv—1916, pp. 983-990**

This paper endeavors to lay out a distribution system that will take care of the greatly increasing demand for power for heating and cooking. Units of load, consumption and revenue were taken from actual tests and applied to definite sections thought to be representative, as containing every class of house, with schools, churches, etc. Results obtained seem to indicate for this class of business a profit at a lower rate. The central station man is advised to make provision for this increased demand when rebuilding in the future.

Discussion, pages 991-1000, by Messrs. D. F. Henderson, E. R. Perry, J. B. Fisken, M. T. Crawford, F. D. Weber, C. R. Collins, W. D. Peaslee, E. G. Robinson, L. T. Merwin, H. W. Buck, S. M. Kennedy, W. L. Chrysler, J. R. King, H. J. Gille and R. Howes.

A general discussion with particular emphasis on the desirability of simpler rates and methods of metering.

UNDERGROUND DISTRIBUTION SYSTEMS

G. J. Newton **Vol. xxxv—1916, pp. 1207-1222**

This paper shows the importance of properly designing an underground distribution system for the district it serves and the particular service it is to supply. Simply placing the wires underground does not constitute an efficient system. Underground distribution is the ultimate solution of the distribution problem that confronts every electric light and power company operating in progressive towns and cities. The suggestions offered are based on many years experience and are aimed to aid particularly in the design and installation of the first system in the smaller cities.

Discussion, pages 1223-1235, by Messrs. T. E. Tynes, A. F. Hovey, F. D. Egan, S. C. Coey, C. A. Menk, H. B. Gear, B. G. Beck, B. W. Gilson, L. Hommel, G. T. Street and F. H. Woodhull.

A discussion of the advantages of single conductor, three-phase cables, type of insulation, location and size of manholes, ventilation of ducts, fireproofing cables and joints, etc.

THE POWER COMPANY'S PROBLEM IN THE ELECTRIC SUPPLY FOR LARGE SINGLE-PHASE LOAD

W. C. L. Eglin **Vol. xxxv—1916, pp. 1289-1292**

The power company must be able to supply energy of uniform pressure, single-phase, two-phase or three-phase, at whatever voltage best suits customer. These conditions best met by polyphase units. When demand for single-phase current is heavy enough to produce unbalance, some means of balancing must be provided. Three methods are discussed Correction for power factor on each individual large consumer's line is suggested.

Discussion incorporated with that of paper by Philip Torchio on "Supply of Single-Phase Loads from Central Stations."

SUPPLY OF SINGLE-PHASE LOADS FROM CENTRAL STATIONS

Philip Torchio **Vol. xxxv—1916, pp. 1293-1301**

American central stations have extensively adopted single-phase distribution from polyphase stations. Individual regulators employed. Generators with good single-phase characteristics or in certain cases generators with kilovolt ampere rating in excess of kilowatt capacity of steam unit are employed. Customers assist balancing by dividing load between phases. Question of power supply to N. Y., N. H. & H. R. R. discussed. Equipment described.

Discussion, (including that of paper by W. C. L. Eglin), pages 1302-1313, by Messrs. W. S. Murray, P. Junkersfeld, D. B. Rushmore, L. E. Imlay, H. R. Summerhayes, N. W. Storer, E. H. Martindale, E. F. W. Alexanderson, J. L. Harper, H. W. Buck, J. E. Kershner, C. F. Scott, W. C. L. Eglin, P. Torchio, F. Osgood and C. F. Harding.

General discussion.

SINGLE-PHASE POWER PRODUCTION

E. F. W. Alexanderson and G. H. Hill **Vol. xxxv—1916, pp. 1315-1327**

The general tendency of electric power supply is toward centralization of stations and to be consistent stations must be standardized. From this standpoint single-phase power can best be supplied from polyphase systems. Operation and theory of phase converters discussed.

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A general discussion of the advantages of various methods of single-phase generation and operation with some facts relative to comparative costs.

16. CONTROL, REGULATION AND SWITCHING

THE LIQUID RHEOSTAT IN LOCOMOTIVE SERVICE

A. J. Hall **Vol. xxxv—1916, pp. 167-171**

A description of the liquid rheostat in locomotive service giving in detail the arrangement of the mechanical parts and means of controlling it.

Discussion, pages 172-173, by Messrs. C. D. Knight and R. E. Hellmund.

A discussion mainly of the liquid rheostat used in mine-hoist service.

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A general discussion of the advantages of various methods of single-phase generation and operation with some facts relative to comparative costs.

RUPTURING CAPACITIES OF OIL CIRCUIT BREAKERS

Stephen Q. Hayes **Vol. xxxv—1916, pp. 1523-1530**

A series of notes on the rupturing capacity of oil breakers. Description of result obtained by root-mean-square of maximum peak of current wave that occurs while breaker is opening multiplied by root-mean-square of open-circuit voltage that occurs immediately after breaker opens. Attention called to different classes of ratings. Recommendations made as to most desirable method of rating and ability of breakers to be re-operative.

Discussion incorporated with that of paper by E. M. Hewlett on "Rating of Oil Circuit Breakers."

RATING OF OIL CIRCUIT BREAKERS

E. M. Hewlett **Vol. xxxv—1916, pp. 1531-1533**

Paper points out several difficulties which are encountered in rating by actual current breakers, but generally favors that these ratings be on the basis of the current to be opened in the arc at the operating voltage of the system.

Discussion, pages 1534-1549, by Messrs. C. Lichtenberg, N. L. Pollard, G. A. Burnham, J. L. Harper, H. W. Buck, J. B. Taylor, K. C. Randall, L. E. Imlay, C. A. Adams, E. M. Hewlett, S. Q. Hayes, H. R. Summerhayes, P. M. Lincoln, L. W. Chubb and P. Lindemann.

A general discussion.

17. TRACTION

OPERATION ON THE NORFOLK AND WESTERN RAILWAY

F. E. Wynne **Vol. xxxv—1916, pp. 147-153**

A description of the great advantages, from an operating standpoint, incident to the inauguration of electric service on the Elkhorn grade of the Norfolk and Western Railway Co. and why it is possible almost to double the capacity of the road by the use of 12 electric locomotives, instead of the 33 Mallet locomotives formerly in service.

Discussion, pages 154-166, by Messrs. A. H. Armstrong, R. E. Hellmund, F. H. Shepard, B. A. Behrend, W. I. Slichter, C. F. Scott, W. Arthur, H. M. Hobart and F. E. Wynne.

A general discussion with particular emphasis on regenerative braking and the operation of liquid rheostat.

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CHATTERING WHEEL SLIP IN ELECTRIC MOTIVE POWER

G. M. Eaton **Vol. xxxv—1916, pp. 175-179**

The paper shows that chattering wheel slip is characteristic of all types of electric motive power. The application of the motive power in the electric and steam drives is compared, and the reasons for the chattering wheel slip and the means of measuring and rectifying the same are given.

Discussion, pages 180-182, by Messrs. S. T. Dodd, W. I. Slichter, C. F. Scott, W. L. Merrill and G. M. Eaton.

A general discussion.

HIGH-VOLTAGE D-C. RAILWAY PRACTISE

Clarence Renshaw **Vol. xxxv—1916, pp. 347-360**

This paper deals with the fundamental differences in apparatus for 1200 or 1500 volts as compared with former 600-volt standards. It points out the tendency to use higher d-c. voltages with the multiplicity of voltages slightly differing such as 2400, 3000, 3600, 4200, etc. It recommends in order to avoid confusion, the establishment at once of a standard high voltage. It is shown that final voltage standards are usually fixed by economic standards rather than physical limitations and 5000 volts is suggested as very satisfactory. The 5000-volt line at Jackson, Michigan, is briefly described.

Discussion, pages 361 and 383, by Messrs. F. J. Sprague, W. J. Davis, Jr., W. B. Potter, Calvert Townley, S. I. Oesterreicher, B. F. Wood, E. V. Pannell, A. H. Armstrong, S. Haar, C. Schwartz, N. W. Storer and C. Renshaw.

A detailed presentation of the arguments for and against the adoption of higher d-c. voltages and standardization.

18. LIGHTING AND LAMPS

ILLUMINATION OF THE PANAMA-PACIFIC INTERNATIONAL EXPOSITION

W. D'A. Ryan **Vol. xxxv—1916, pp. 757-782**

This paper describes the system of lighting adopted for the P-P. I. E., which was generally conceded to have initiated a new era in the art of illumination. From a narrow engineering point of view the lighting would have been regarded as inefficient, but the object striven for was to suppress high intrinsic brilliancy, while bringing out the architectural beauties of the exposition structures in the most effective manner.

No discussion.

20. MISCELLANEOUS APPLICATIONS OF ELECTRICITY

THE TRUE NATURE OF SPEECH

J. B. Flowers **Vol. xxxv—1916, pp. 213-231**

A proof that speech is a rapid variation in the intensity of the voice and mouth tones according to definite sound patterns called letters of the alphabet. Photographs are taken with aid of string-galvanometer of each letter of the alphabet. From the curve the phonographic alphabet is obtained by measuring the variations in intensity of the main tone of the record.

A design for a voice-operated phonographic alphabet writing machine is described.

Discussion, pages 232-248, by Messrs. H. B. Williams, L. T. Robinson, A. C. Crehore, W. Maver, Jr., W. J. Hammer, L. W. Chubb, C. A. Adams, J. B. Taylor and J. B. Flowers.

A general discussion including the development of the theory of the string galvanometer.

ELECTRIC DRIVE FOR REVERSING ROLLING MILLS

Wilfred Sykes and David Hall **Vol. xxxv—1916, pp. 501-519**

This paper answers some of the questions which have arisen in the rapid displacement of steam drive by electric drive for reversing rolling mills, and describes the constructions which have been found desirable.

Discussion, pages 520-537, by Messrs. K. A. Pauly, E. S. Jeffries, D. M. Petty, R. Tschentscher, H. D. James, F. G. Liljenroth, B. Wiley, H. S. Page, P. Lindemann, A. Gray and W. Sykes.

A discussion of the relative merit of steam and electric drive for reversing mills. Statistics of installation at Steel Company of Canada. Comparison of European and American practise.

MOTOR EQUIPMENTS FOR THE RECOVERY OF PETROLEUM

W. G. Taylor **Vol. xxxv—1916, pp. 539-552**

This paper presents data covering the horse power requirements and kilowatt-hour consumption for the various operations in drilling and maintaining producing oil wells. The use of the slip-ring induction motor for drilling, pumping and cleaning wells. Special controllers and resistance. Pumping, cleaning and "pulling" rods by a Y-delta or two-speed machine.

Discussion, pages 553-554, by Messrs. F. Woodbury and A. M. Dudley. General discussion.

SOME FEATURES OF DOMESTIC ELECTRIC COOKING AND HEATING

H. B. Peirce **Vol. xxxv—1916, pp. 1001-1011**

From tests made on a number of domestic cooking and heating installations, it would appear that electric cooking has a better load factor than a lighting load and that this factor improves as the number of ranges increases. The errors incident to these tests are discussed. Suggestions are made for checking these results by others. In the heating field, the effect of water heaters superimposed on range loads is discussed in relation to their effect on the central station loads and income.

Discussion, pages 1012-1015, by Messrs. J. B. Fisken, C. E. Magnusson, W. D. Peaslee, L. F. Curtis, R. W. Pope, E. R. Perry, H. F. Holland and H. J. Gille.

A general discussion.

21. TELEPHONY AND TELEGRAPHY

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A discussion of the various factors involved in the selection of a wave-shape standard and the penalizing of upper harmonics. An appeal for cooperation between power companies, telephone companies and manufacturers.

22. MISCELLANEOUS TOPICS AND INSTITUTE AFFAIRS

THE MUNICIPALLY-OPERATED ELECTRICAL UTILITIES OF WESTERN CANADA

A. G. Christie **Vol. xxxv—1916, pp. 33-87**

The paper discusses a number of public utilities in various cities in Western Canada. The characteristics of these cities are reviewed and a brief outline of equipments of the various plants is given. The costs and methods of financing these utilities are discussed at considerable length and the charges for various services are summarized.

Discussion, pages 88-98, by Messrs. P. Betts, H. G. Stott, R. P. Bolton, E. J. Cheney, C. H. Sharp, A. Reid and A. G. Christie.

A general discussion of the advantages and disadvantages of municipal ownership of public utilities and methods of financing them.

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G. M. Eaton **Vol. xxxv—1916, pp. 175-179**

The paper shows that chattering wheel slip is characteristic of all types of electric motive power. The application of the motive power in the electric and steam drives is compared, and the reasons for the chattering wheel slip and the means of measuring and rectifying the same are given.

Discussion, pages 180-182, by Messrs. S. T. Dodd, W. I. Slichter, C F. Scott, W. L. Merrill and G. M. Eaton.

A general discussion.

A METHOD OF DETERMINING THE CORRECTNESS OF POLYPHASE WATT-METER CONNECTIONS

W. B. Kouwenhoven **Vol. xxxv—1916, pp. 183-206**

A description of a method of checking the correctness of the connections of a polyphase watt-hour meter and proof that the methods most commonly used are unreliable. Rules are worked out that make the rectification of incorrect connections simple. Another method is described which may be used on balanced or unbalanced three-phase circuits at any power factor, providing the opening of one phase at a time is permissible.

Discussion, pages 207-211, by Messrs. W. H. Pratt, G. A. Sawin, L. W. Chubb, C. A. Adams and W. B. Kouwenhoven.

A general discussion.

THE TRUE NATURE OF SPEECH

J. B. Flowers **Vol. xxxv—1916, pp. 213-231**

A proof that speech is a rapid variation in the intensity of the voice and mouth tones according to definite sound patterns called letters of the alphabet. Photographs are taken with aid of string-galvanometer of each letter of the alphabet. From the curves the phonographic alphabet is obtained by measuring the variations in intensity of the main tone of the record.

A design for a voice-operated phonographic alphabet writing machine is described.

Discussion, pages 232-248, by Messrs. H. B. Williams, L. T. Robinson, A. C. Crehore, W. Maver, Jr., W. J. Hammer, L. W. Chubb, C. A. Adams, J. B. Taylor and J. B. Flowers.

A general discussion including the development of the theory of the string galvanometer.

THE FUTURE OF WATER POWER IN THE UNITED STATES

Charles W. Comstock **Vol. xxxv—1916, pp. 249-260**

A compilation of figures showing the total fixed installed primary power in the United States and similar figures for the total installed water power. With these figures, those compiled by the Commissioner of Corporations are summarized and compared. The geographic distribution of installed water power is studied together with the development of water power between 1889 and 1909. The author next takes up the possibilities of water power development and makes an appeal for a federal policy of encouraging business enterprise instead of obstructing it.

No discussion.

IRON LOSSES IN DIRECT-CURRENT MACHINES

B. G. Lamme **Vol. xxxv—1916, pp. 261-286**

It is shown that no great accuracy is practicable in the calculation of actual iron losses, except in special cases. A brief explanation of several causes of variation in losses is given.

The four principal sources of core loss are considered, namely—armature-ring loss, armature-tooth loss, eddy currents in buried conductors, and pole-face losses. Under eddy current losses an explanation is given of certain losses not usually taken into account with a crude method of calculation and some tabulated results.

Under pole-face losses an empirical formula is given, also tabulated results.

The effect of load on losses is discussed and some of the effects of flux distortion on losses are shown.

Discussion, pages 287-299, by Messrs. H. F. T. Erben, W. S. Moody, W. B. Potter, F. H. Kierstead, H. M. Hobart, W. J. Foster, J. L. Burnham, L. T. Robinson, A. S. Langsdorf and B. G. Lamme.

A general discussion of iron losses in d-c. machines and transformers.

THE INFLUENCE OF FREQUENCY OF ALTERNATING OR INFREQUENTLY REVERSED CURRENT ON ELECTROLYTIC CORROSION

Burton McCollum and G. H. Ahlborn **Vol. xxxv—1916, pp. 301-327**

This paper describes experimental work done to determine the coefficient of corrosion of iron and lead in soil with varying frequencies of alternating or reversed current with 60 cycles per second as the highest frequency and a two-week period as the lowest. Some d-c. tests being made as a check on the methods.

The importance of the conclusions reached grows out of the fact that there are large areas in practically every city in which the polarity of the underground pipes reverses with periods ranging from a few seconds to an hour or more due to the shifting of railway loads. Corrosion under such conditions is shown to be much less than has generally been supposed.

Discussion, pages 328-345, by Messrs. P. Torchio, A. Maxwell, A. F. Ganz, J. L. R. Hayden, S. M. Kintner, C. Hering, A. P. Way, C. B. Martin, T. M. Roberts, L. W. Chubb, T. Spooner, M. Toch and B. McCollum.

A general discussion of electrolytic corrosion and methods of mitigation.

ELECTROCHEMICAL INDUSTRIES AND THEIR INTEREST IN THE DEVELOPMENT OF WATER POWER

Lawrence Addicks **Vol. xxxv—1916, pp. 383-392**

A presentation of the great value of the electrochemical industries to this country and their fundamental interest in cheap power. They offer the almost ideal power load but must be located strategically as regards supplies and markets. Niagara power is not cheap enough or sufficient for their needs under present conditions. Great expansion should follow the development of cheaper power particularly in that vital field, the nitrate industry. An appeal is made for a more liberal water power policy on the part of the government.

Discussion incorporated with that of paper by L. B. Stillwell on "Relation of Water Power to Transportation."

WATER POWER DEVELOPMENT AND THE FOOD PROBLEM

Allerton S. Cushman **Vol. xxxv—1916, pp. 393-402**

The great increase of the population of the United States, has been chiefly in the urban districts, resulting in a continuously growing demand for food with a relatively small proportion of the population as food producers.

To increase production per acre requires the production of nitrogen, one of the three principal fertilizer ingredients. This is distinctly a water power proposition involving the fixation of atmospheric nitrogen. More than 80 per cent of mixed fertilizers produced in the United States is used east of the Allegheny Mountains, and for the fertilizer problem water power must be developed where the demand for the fertilizer exists. A proper plan of water power development will have a profound influence on the development and distribution of cheap fertilizer ingredients.

Discussion incorporated with that of paper by L. B. Stillwell on "Relation of Water Power to Transportation."

RELATION OF WATER POWER TO TRANSPORTATION

Lewis B. Stillwell **Vol. xxxv—1916, pp. 403-416**

The relative importance of water power in its relation to transportation, as depending upon its cost and the cost of competing steam power.

Ratio of cost of fuel for locomotives in country as a whole, in various sections, and in a number of different railroads, to total cost of operation.

Effect of recent progress in art of producing electric power by steam upon water power values.

Power and transportation development on navigable streams.

Illustrations of the limit of investment in developing a water power, as fixed by cost of competing steam power.

Comparative cost of canals and railroads.

Illustrations of comparative speed and power consumption in railroad and canal operation.

Discussion (including that of papers by L. Addicks and A. S. Cushman), pages 417-430, by Messrs. D. B. Rushmore, F. A. Lidbury, H. G. Stott, G. Dunn, J. B. Whitehead, L. H. Baekeland, J. J. Carty, L. S. Randolph, L. Addicks, A. S. Cushman and L. B. Stillwell.

A general discussion of the principal features of the three papers.

WATER POWER AND DEFENSE

W. R. Whitney **Vol. xxxv—1916, pp. 431-439**

As the United States has no adequate domestic source of fixed nitrogen, and as nitric acid is an absolute necessity in the manufacture of explosives and in the production of dye stuffs, the Army, Navy Agriculture and Interior Departments should immediately cooperate in determining course to be taken.

It is pointed out that failure to establish such an industry has been due to the proximity of Chile and the impossibility of competing with the cheap water powers of Scandinavia. National safety demands the development of such an industry whether it be supporting or not, but once established the products would be of the greatest value in times of peace, and many other industries would be stimulated.

Discussion incorporated with that of paper by Gano Dunn on "The Water Power Situation, Including Its Financial Aspect."

THE WATER POWER SITUATION, INCLUDING ITS FINANCIAL ASPECT

Gano Dunn **Vol. xxxv—1916, pp. 441-456**

The endeavor of this paper is to present, from the point of view of the engineer, certain aspects of the attitude of capital towards water powers. Actual and threatened laws, popular prejudices, unprofitable developments in the past, and also physical and natural difficulties which handicap hydroelectric as compared with steam-electric plants make a reasonable profit essential to induce investment. The rising cost of water power and the decreasing cost of steam power. Length of time a permit or franchise may run before recapture clauses take effect. Water power developed as a matter of conservation of coal supply.

Discussion (including that of paper by W. R. Whitney), pages 457-477, by Messrs. F. A. Lidbury, L. Addicks, G. Dunn, J. H. Finney, L. H. Baekeland, C. G. Atwater, C. Townley, G. R. Smith, D. B. Rushmore, O. T. Crosby.

A general discussion from the viewpoints of the engineer, financier, manufacturer and congressman.

THE RELATION OF PURE SCIENCE TO INDUSTRIAL RESEARCH

President's Address

J. J. Carty **Vol. xxxv—1916, pp. 479-488**

STANDARDIZATION

C. Le Maistre **Vol. xxxv—1916, pp. 489-496**

A general review of development of standardization committees and organizations here and abroad. A citation of the many advantages of proper standardization and an appeal for universal cooperation. Particular reference is given to standardization of electrical machinery with emphasis laid on the adoption of a standard temperature rise basis.

Discussion, pages 497-500, by Messrs. C. H. Sharp, F. Osgood, C. P. Steinmetz, C. Le Maistre and C. A. Adams.

A general discussion.

EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED STATIONARY INDUCTION APPARATUS

V. M. Montsinger **Vol. xxxv—1916, pp. 599-626**

This paper is divided into three parts, as follows: (1) A general review of the principal laws of the dissipation of heat,—radiation, conduction and convection. (2) The development of a simple formula for the effect of altitude on the cooling of surfaces of different shapes. (3) A general discussion of the method of conducting experimental observations at different altitudes on three different shaped surfaces.

Discussion, pages 627-633, by Messrs. R. W. Sorensen, A. Gray and V. M. Montsinger.

A general discussion of methods and results obtained.

EXPERIENCES IN TESTING PORCELAIN

E. E. F. Creighton **Vol. xxxv—1916, pp. 739-744**

The results of numerous experiences in testing porcelain insulators particularly in regard to porosity, absorption of water, surface leakage and dielectric losses. Considerable energy is required to drive moisture out of a porous insulator and it has been found best to restrict the oscillator testing to dry porcelain, whereas the wetter the porcelain the more effective is the 60-cycle test.

Discussion incorporated with that of paper by R. H. Marvin on "A New Method of Grading Suspension Insulators."

A NEW METHOD OF GRADING SUSPENSION INSULATORS

R. H. Marvin **Vol. xxxv—1916, pp. 745-752**

Attention is drawn to the known disadvantages of the uneven distribution of voltage in long strings of disks. The general theory showing how the distribution is determined by the various capacities of the units is given. It is shown how the distribution can be improved by grading, or varying the internal capacity of the units.

The proposed method of grading consists in placing flat metal rings on the insulator, around the cap and stud respectively, the porcelain disk being enlarged for this purpose.

A simple method of measuring the voltage distribution is described using a single needle gap.

The results of tests with and without grading are given, the graded strings showing a decidedly better distribution of voltage.

Discussion, pages 753-755, by Messrs. F. W. Peek, Jr., and E. E. F. Creighton.

A general discussion.

ILLUMINATION OF THE PANAMA-PACIFIC INTERNATIONAL EXPOSITION

W. D'A. Ryan **Vol. xxxv—1916, pp. 757-782**

This paper describes the system of lighting adopted for the P-P. I. E., which was generally conceded to have initiated a new era in the art of illumination. From a narrow engineering point of view the lighting would have been regarded as inefficient, but the object striven for was to suppress high intrinsic brilliancy, while bringing out the architectural beauties of the exposition structures in the most effective manner.

No discussion.

SUGGESTIONS FOR ELECTRICAL RESEARCH IN ENGINEERING COLLEGES

V. Karapetoff **Vol. xxxv—1916, pp. 895-910**

This paper gives a list of topics in electrical engineering suitable for thesis, research and advanced study. A plea is made for systematic research, each college specializing year after year in only a few topics. Cooperation is urged with individual inventors and investigators. Various types of investigation are enumerated, such as invention, experimental study, theoretical study, library search, and compilation of data.

Discussion, pages 911-923, by Messrs. J. B. Whitehead, A. E. Flowers, C. E. Skinner, F. C. Caldwell, E. E. Creighton, D. D. Ewing, C. F. Harding, N. S. Diamant, J. J. Carty, D. H. Braymer, A. A. Nims and A. Gray.

A general discussion from the viewpoint of the college professor, inventor and manufacturer.

TRACTIVE RESISTANCES TO A MOTOR DELIVERY WAGON ON DIFFERENT ROADS AND AT DIFFERENT SPEEDS

A. E. Kennelly and O. R. Schurig **Vol. xxxv-1916, pp. 925-953**

A complete report on an investigation of tractive resistances of urban roads to a motor delivery wagon equipped with solid rubber tires. The "tractive resistance" as used in this paper, includes still-air resistance, but does not include wind resistance and the resistance internal to the truck. The test truck is fully described. The results included are (1) overall efficiency of truck mechanism and (2) tractive resistances of a number of typical urban roads. The components of tractive resistance for a typical road are also given.

Discussion, pages 954-955, by Messrs. A. A. Nims and O. R. Schurig.

A discussion of "vehicle efficiency," "road resistance," "air resistance," etc.

APPLICATION OF A POLAR FORM OF COMPLEX QUANTITIES TO THE CALCULATION OF ALTERNATING-CURRENT PHENOMENA

N. S. Diamant **Vol. xxxv—1916, pp. 957-978**

In the calculation of a-c. phenomena by means of complex quantities, as a rule, the rectangular components of the vector are used. A simple method for dealing directly with the vectors themselves is described and consists in introducing the operator j^n, where n, contrary to ordinary usage, may be any positive or negative fraction. For convenience of reference a summary of formulas is given and also a very short bibliography.

Discussion, pages 979-981, by Messrs. A. Gray, E. E. F. Creighton, J. B. Whitehead, E. H. Colpitts and N. S. Diamant.

A general discussion of the various mathematical determinations.

SOME FEATURES OF DOMESTIC ELECTRIC COOKING AND HEATING

H. B. Peirce **Vol. xxxv—1916, pp. 1001-1011**

From tests made on a number of domestic cooking and heating installations, it would appear that electric cooking has a better load factor than a lighting load and that this factor improves as the number of ranges increases. The errors incident to these tests are discussed. Suggestions are made for checking these results by others. In the heating field, the effect of water heaters superimposed on range loads is discussed in relation to their effect on the central station loads and income.

Discussion, pages 1012-1015, by Messrs. J. B. Fisken, C. E. Magnusson, W. D. Peaslee, L. F. Curtis, R. W. Pope, E. R. Perry, H. F. Holland and H. J. Gille.

A general discussion.

INSULATOR FAILURES UNDER TRANSIENT VOLTAGES

W. D. Peaslee **Vol. xxxv—1916, pp. 1187-1194**

This paper presents the results of recent investigations on the failure of insulators under impact and combined impact and normal frequency voltages. Microphotographs are included. The breakdown of a dielectric involves energy which is a time function, and the importance of the duration of the stress in determining the magnitude of the voltage necessary to puncture an insulator are discussed. The importance of the elimination of air holes and defects in porcelain is shown. Some essential features of a successful line insulator are stated.

Discussion, pages 1195-1205, by Messrs. J. B. Fisken, W. D. Peaslee, R. Howes, L. T. Merwin, H. J. Ryan, R. W. Mastick, R. M. Boykin, A. A. Miller and E. E. F. Creighton.

A general discussion including experiences of certain power transmission lines.

ELECTRICAL MACHINERY TESTS AND SPECIFICATIONS BASED ON MODERN STANDARDS

H. M. Hobart **Vol. xxxv—1916, pp. 1359-1367**

Comparisons are made of the standardization rules for electrical machinery now in force in various countries showing that machinery built in conformance with the American rules will usually also conform with rules employed in other countries. Suggestion is made that 55 degrees could be employed as the ambient temperature of reference for tropical ratings. Attention is called to a series of acceptance tests on some large waterwheel generators and to the temperature results obtained by making cyclic heat runs on these machines.

No discussion.

THE EFFECT OF RECENT DECISIONS ON THE WORK OF INVENTORY AND APPRAISAL

Philander Betts **Vol. xxxv—1916, pp. 1369-1374**

In order that inventories and appraisals shall be useful in determining all the appropriate elements of value, they must be classified as to age, condition, use, and extent of use in each class of service.

Discussion, incorporated with that of paper by Julian Loebenstein on "Growth and Depreciation."

CONTINUOUS INVENTORIES: THEIR PREPARATION AND VALUE

Harry E. Carver **Vol. xxxv—1916, pp. 1375-1387**

A discussion of the advisability of attempting a continuous inventory, giving possible uses and advantages to be derived therefrom. Also, the preparation of such an inventory. Suggestions for the division of property into four general groups for that purpose, outlines of general forms and methods for collecting and recording data required.

Discussion incorporated with that of paper by Julian Loebenstein on "Growth and Depreciation."

GROWTH AND DEPRECIATION

Julian Loebenstein **Vol. xxxv—1916, pp. 1389-1407**

It is generally assumed that a complex utility property will depreciate to an approximately fixed per cent condition. This is shown by theoretical and actual curves to be incorrect. It is shown that the manner of the company's growth affects its per cent condition.

The necessity of reserves, the manner in which they may be kept and the return which should be allowed on them, whether reinvested or not, is discussed. Several commission and court decisions are quoted to show the tendency to disallow a return on a reserve and arguments are presented in refutation of the decisions.

Discussion (including that of papers by Philander Betts and Harry E. Carver), pages 1408-1436, by Messrs. W. B. Jackson, G. W. Whittemore, D. B. Rushmore, E. J. Cheney, W. S. Franklin, P. Betts, H. E. Carver, W. R. McCann, F. Gill, L. R. Nash, F. C. Merriell and J. Loebenstein.

A general discussion of factors involved in the three papers.

RUPTURING CAPACITIES OF OIL CIRCUIT BREAKERS

Stephen Q. Hayes **Vol. xxxv—1916, pp. 1523-1530**

A series of notes on the rupturing capacity of oil breakers. Description of result obtained by root-mean-square of maximum peak of current wave that occurs while breaker is opening multiplied by root-mean-square of open-circuit voltage that occurs immediately after breaker opens. Attention called to different classes of ratings. Recommendations made as to most desirable method of rating and ability of breakers to be re-operative.

Discussion incorporated with that of paper by E. M. Hewlett on "Rating of Oil Circuit Breakers."

RATING OF OIL CIRCUIT BREAKERS

E. M. Hewlett **Vol. xxxv—1916, pp. 1531-1533**

Paper points out several difficulties which are encountered in rating by actual current breakers, but generally favors that these ratings be on the basis of the current to be opened in the arc at the operating voltage of the system.

Discussion, pages 1534-1549, by Messrs. C. Lichtenberg, N. L. Pollard, G. A. Burnham, J. L. Harper, H. W. Buck, J. B. Taylor, K. C. Randall, L. E. Imlay, C. A. Adams, E. M. Hewlett, S. Q. Hayes, H. R. Summerhayes, P. M. Lincoln, L. W. Chubb and P. Lindemann.

A general discussion.

ol. 35
916

TOPICAL INDEX.

- A-C. generators, temperature guarantees (See Temperature guarantees, etc.)
  - motors, oil wells (See Motors, oil wells, etc.)
  - phenomena, calculation, complex quantities, polar form 957
    - complex quantities, polar form, addition and subtraction 962
    - complex quantities, polar form, bibliography 977
    - complex quantities, polar form, expression for power 963
    - complex quantities, polar form, general principles 959
    - complex quantities, polar form, illustrative problems 966
    - complex quantities, polar form, multiplication and division 960
- Admittance, wave form standard, characteristics 1155
  - condenser type, objections 1157
  - distortion factors, formulas 1167
    - numerical values 1173
  - harmonics, penalty curves 1172
  - interference coefficients 1174
  - measurements 1168
  - R C standard, characteristic curves, R variable 1160
  - RLC standard, characteristic curves, variable L, R constant 1163
  - RLC standard, characteristic curves, variable R, L constant 1162
  - RLC standard, important requirements 1166
  - simple and complex standard circuits 1158
- Air, corona, effect of density 788
    - visual, data 787
  - effect high continuous voltages 783
  - spark-over voltages, concentric cylinders 789
    - needle gaps 786
    - spheres 785
- Alabama Power Co., report on grounded neutral 581
- Altitude, effect on temperature rise, electrical apparatus. (See Temperature, operating, etc.)
- Appraisal and inventory, recent decisions, effect of (See Inventory and appraisal, recent decisions, etc.)
- Arcing ground suppressor 699 719
- Arresters, aluminum cell 699
  - lightning, determining effectiveness of 659
- Artificial transmission line, adjustable constants 1137
- Asphalt roads, tractive resistances, motor truck 941
- Balancers, single-phase, essential requirements 1341

Barometric pressure, effect on temperature rise, stationary induction apparatus (See Temperature, operating, altitude effect, etc.)
Blooming mill, reversing, electric drive, statistics 502
Brick-block road, tractive resistance, motor truck 943
Budapest City Railroad, d-c., high voltage 369
Bus, generator, scheme of Public Service Electric Co. 701
Cables, insulated, lead covered, temperature rise 1017
split conductor, use 725
temperature rise, carrying capacity 2-conductor concentric 1037
2-conductor flat and 3-conductor sector 1037
reduction factors 1050
duct lines 1028
forced ventilation 1047
water cooled 1046
early investigations 1018
effect of adjacent cables, equations 1049
effect of short-circuited lead sheaths 1046
final rise 1034
hot spots due to steam lines 1043
maximum current carrying capacity, multiple-conductor cable 1027 1035
maximum current carrying capacity one-conductor cable 1024 1025
overload or intermittent rating 1030
rate 1032 1038
rating of cables 1019
sheath currents 1027
surface thermal conductivity 1020
thermal conductivities, graphic method 1034
paper-insulated one-conductor lead-covered 1024
variable air temperature, duct line 1041
Canadian electrical utilities, municipal (See Public utilities, etc.)
Central station power, single-phase 1329
Ceramics, durability factor, porcelain suspension insulators (See Insulators, porcelain suspension, etc.)
Chicago and Interurban Traction Co., report on grounded neutral 580
Cinder and gravel roads, tractive resistances, truck 946
Circuit breakers, oil, rating 1531
distress definition 1536
factor of safety 1541
low vs. high-voltage arcs 1541
physical dimensions factor 1533
power factor 1535
reactors 1533
rupturing capacity 1523
1,425,000 kv-a. test 1530
class ratings 1525
effect of location 1524
maximum current vs. maximum kv-a. rating 1528
ratings, automatic and non-automatic 1525
reoperation 1528
symmetrical vs. unsymmetrical wave 1526
tank dimensions factor 1527
Complex quantities, polar form, application to solution of a-c. phenomena 957
Conductivity, thermal, cylinders, infinite length (cables) 1019

Conductors, split, use 725
steel (See Transmission, conductors, steel, etc.) 1237
Converters, phase, action of, explanation 1352
current relations 1352
theory of 1318
synchronous, protection, after service interruption 640
Cooking, electric, demand factor, apartment house, curve 1005
curves 1005
load factor 1002
range load curves 1003
power rates 989
Copper losses, d-c. machines, armature eddy current, estimated vs. calculated,
table 274
formula 272 273
loss at no-load 269
Corona, detection; comparison of electroscope, galvanometer and telephone method 820
electroscope 812
galvanometer 813
observed and calculated values, comparison 821
telephone 814
voltmeter 809
methods of observation 812
principle 811
Cost, artificial transmission line 1141
comparative single-phase power generation 1348 1357
insulator testing, telephone method 1106
municipal lighting and railway power, Canada 64
power, Niagara 387
per kw-hr., public utilities, Canadian, table 53
single-phase, Niagara 1307
rolling mill, reversing drive, steam vs. electric 506
Crest voltmeters (See Voltmeters, crest, etc.)
Currents, impulse, periodic and non-periodic vs. spacic and non-spacic 30
theory 1
boundary conditions 25
constants 23
cumulative oscillations 24
distortion constant 14
energy dissipation constant 15
energy transfer constant 15
extremely high frequencies 22
quarter-wave oscillations 22
terminal conditions 23
Cyclograph, cathode ray 141
D-C. railway practise, high-voltage (See Railways, d-c. etc.)
Defense vs. water power developemnt (See Water power development, etc.)
Depreciation and growth (See Growth and depreciation)
Dielectric strength, absorption phenomena 805
air, oil and solid insulations 783
variation with thickness, explanation 804
Dielectrics, research subjects 909
Direct-current machines, iron losses (See Iron losses, etc.)
Distortion factor, differential, definition 1157
Distribution, domestic power, commercial and engineering standpoint 983
individual residence transformers, advantages 992
map of system 984
underground, 3-conductor cable, maximum sizes 1235

ol. 35
916

- Distribution, underground (*continued*)
  - advantages 1209
  - cable, installing 1218
    - sizes 1215
  - conduit, location 1220
    - size 1230
    - system 1219
  - design, load records 1210
  - economy, factors concerned 1213
  - load maps 1211 1214
  - location of trunk ducts under service boxes 1224
  - manholes, fireproofing cables 1232
    - number 1232 1234
  - paper-insulated cable 1222
  - reliability, factors concerned 1213
  - schemes of distribution 1211
  - steel mills 1224
    - disadvantages 1226
    - duct foundations 1227
    - single vs. 3-conductor cable 1228
  - sub-surface obstructions, map 1221
  - subway equipment 1217
  - system subdivisions 1215
  - transformer vaults, ventilation 1229
- Domestic power, distribution systems (See Distribution, domestic power, etc.)
- Efficiency, mechanism, overall, electric truck 935
- Einthoven galvanometer 217
  - motion of string, equation 237
    - varying frequency, curves 238
- Electric circuit, capacity in series, application of 29 31
  - diagram 28
  - voltage and current equations 28
  - drive, rolling mills, reversing (See Rolling mills, reversing, etc.)
  - heating and cooking, some features of 1001
  - lighting, research subjects 906
  - machinery, specifications, modern standards (See Specifications, electric machinery, etc.)
  - railroad, Norfolk and Western, Operation (See Railroad, electric, etc.)
  - truck, overall efficiency, driving mechanism 935
  - valve, frequency range 135
- Electrical apparatus, temperature rise, effect of altitude (See Temperature, operating, etc.)
  - machinery, temperature distribution (See Temperature distribution, etc.)
  - research, engineering colleges, suggestions 895
  - utilities, municipal, Canadian, western (See Public utilities, etc.)
- Electrochemical industries, cooperative power development 391
  - location, factors involved 389
  - products, brief review of 386
  - various products, power consumption 387
  - water and power development, interest 385
- Electrolysis, coefficient of corrosion, definition 301
  - iron, variation of potential between bonds of pipe or rail 339
    - water rheostats 339
    - and lead, advisability of reversing trolley potentials periodically 328

Electrolysis, iron and lead (*continued*)
    apparent current densities met in practise 329
    coefficient of corrosion, various conditions, curve 325
    complete tests, accuracy of results 315
        arrangement of tests 309
        chemicals and electrodes 311
        cleaning of electrodes 313
        conditions 310
        correction and reduction factors 314
        current measurements 314
        electrolyte used 309
        frequency and current density 312
        iron electrodes in sodium carbonate soil 320
        lead electrodes in sodium carbonate soil 321
        60 and 15-cycle tests 316
        1-sec. and 6-sec. period tests 316
        one and ten minute period tests 316
        One hour, 48 hour and weekly period tests 317
        tabular summary of tests 319
    effect of circulation of electrolyte 305
    effect of circulation of electrolyte, 60-cycle and 20-cycle current table 307
    effect of circulation of electrolyte, 24-hour reversals, table 308
    effect of current reversal on resistance 336
    effect of gas formation in electrolyte.331 338
    effect of valency of metals on corrosion 333
    frequency limit of corrosion 332
    influence of frequency 301
    main causes 302
    pitting 335
    theories advanced 303
  iron embedded in concrete 336
  nickel steel alloys and boiler plate 341
  various alloys, electrolyte of 2 per cent sodium carbonate 340
Electroscope, corona detection 812
Exciters, connection scheme, Public Service Electric Co 703
Experiments, insulators, porcelain suspension (See Insulators, porcelain suspension, etc.)
Faulty cable localizer 700
Food problem vs. water power development (See Water Power development, etc.)
Frequency, effect on electrolysis of iron and lead (See Electrolysis, iron and lead, etc.)
    high, suppression of surges, use of parallel grounded wires (See Wires, parallel grounded, etc.)
Future of water power in the United States 249
Galvanometer, corona detection 813
    Einthoven 217
Generators, 3-phase, protection, opening field circuit, diagram of connections 639

Generators, 3-phase protection (*continued*)
relays........................ 636
voltage reduction, opening exciter field........ 638
opening generator field... 638
a-c., temperature guarantees (See Temperature, guarantees, etc.)
air-washer, Public Service Electric Co............... 713
d-c., speed-output curves......................... 515
research subjects................................ 902
single-phase, theory.............................. 1332
turbo, temperature conditions, rotors............... 1497
stators............... 1493
Granite block road, tractive resistance, motor truck.............. 943
Grounded neutral, high-tension transmission, experiences (See Transmission, high-tension, etc.)
Growth and depreciation.................................. 1389
anticipated depreciation............... 1410
contractors profits..................... 1417
depreciation definitions............... 1409
fund, allowable return, justice of................. 1404
expense of depreciation................. 1411
gold depreciation factor............1416 1418
increasing investment, ten years......... 1396
influence of growth..................... 1414
investment cost......................... 1417
liquid depreciation reserve fund......... 1390
per cent condition...................... 1396
reserve fund, laying aside and use....... 1401
structural value......................... 1411
theoretical depreciation................. 1410
uniform investment, five years.......... 1392
ten years......... 1391
value cure, composite theoretical, St. Louis United Railways............... 1398
Harmonics, high-tension transmission, neutral grounded.......... 596
Heat, radiation, laws....................................... 601
conduction, laws... 603
convection, laws... 603
Lorenz law.................................. 604
dissipation, tank surfaces, calculation.................... 610
Heating, electric, load factor.............................. 1002
power rates.. 989
Helmholtz formula, resonance, spherical cavity................ 226
High frequency surges, suppression by parallel grounded wires (See Wires, parallel grounded, etc.)
High-tension insulators, defective, testing for (See Insulators, high tension, defective, etc.)
High voltage, measurement................................... 119
Illumination, Panama-Pacific International Exposition........... 757
P. I. E., art gallery, non-glare.................. 767
artistic reflections, flood and relief lighting.. 776
banner and cartouche lighting standards.... 763
cascade lighting, concealed............. 777
changeability of effects................ 778
combination fountain and light sources..... 771
curvature, preservation................. 777
electric kaleidoscope................... 765
electric-steam color scintillator........... 762
general lighting and power data........... 780
ground and building plan................ 779

Illumination, P. I. E. (*continued*)
high bay lighting........................ 769
large auditoriums, indirect lighting........ 766
"life-within" effects..................... 770
"Novagem" jewels......................... 761
open court lighting, creation of mystery.... 775
relief wall lighting, concealed sources...... 773
total power, gas and electric.............. 759
tower illumination........................ 760
Impulse currents, theory........................... 1
general.................................... 10
non-periodic............................... 12
periodic................................... 17
types of current........................... 2
distributed constants in a-c. circuit 9
d-c. circuit 5
massed constants in d-c. circuit.... 4
Induction apparatus, temperature rise, effect of altitude.......... 599
Inductive interference, analysis of noise currents............... 1092
angular crossings....................... 1094
barrelling, continuous and non-continuous. 1058
coefficients, determination, instrument diagram................ 1175
various generators.......... 1176
committee report........................ 1171
continuous corona discharge.............. 1089
crossovers.............................. 1062
cross-talk.............................. 1061
discontinuity points..................... 1061
factors involved......................... 1052
future prospects......................... 1054
generator wave form..................... 1088
grounded neutral systems................ 1063
star-star and star-delta......... 1064
higher harmonics........................ 1055
metallic balanced circuits................ 1178
parallelism, data required............... 1078
exposure chart.. 1080
general route map.......... 1085
power circuit diagram......... 1082
symbols used... 1084
particular cases solved, system with grounded neutral at one point only..... 1071
particular cases solved, ungrounded power system.................................. 1075
penalizing harmonics, effect on cost of generators............................ 1180
power circuit factors to be considered..... 1053
practical problem........................ 1051
series impedance in power circuit.....1088 1093
spacing and configuration of power wires.. 1056
telephone circuits, drainage devices....... 1183
transpositions, exposed line systems....... 1065
particular cases solved, three power circuits.......... 1068
power and telephone circuits.................. 1057
rotation of............... 1059

Inductive interference, transpositions (*continued*)
whole-line ... 1067
unbalanced exposure ... 1060
unusual conditions on power circuits ... 1055
wave form, effect of length of transmission line ... 1181
transmission network complications ... 1182
Industrial power, research subjects ... 907
research, relation of pure science (President Carty's address) ... 479
Insulation, high-voltage, effect ... 783
diagram of connections ... 784
resistance recorder, use by Public Service Electric Co.. 712
Insulations, solid, high continuous voltages, effect ... 792
varnished cambric, puncture voltages ... 794
variation with time and temperature ... 795
wet, break-down voltages ... 798
Insulators, dielectric strength, effect of temperature ... 1199
failure, conditions to be avoided ... 1192
structure under microscope ... 1191
transient voltages ... 1187
air-break vs. oil-break switches ... 1200
single vs. oscillating discharge 1205
sphere-gap-horn-gap ... 1201
superposed on normal wave .. 1189
types tested ... 1190
Washington Water Power Co's experience ... 1195
high-tension, defective, megger test for ... 1097
oscillation transformer test ... 1096
telephone receiver test, apparatus ... 1097
telephone receiver test, check methods ... 1102
telephone receiver test, classification of noises ... 1101
telephone receiver test, cost ... 1106
telephone receiver test, defective pin-type ... 1126
telephone receiver test, depreciation data ... 1107
telephone receiver test, limitations ... 1123
telephone receiver test, Pacific Gas & Electric Co. ... 1118
telephone receiver test, porous units ... 1128
telephone receiver test, results. 1105
telephone receiver test, theory of action ... 1100
testing for ... 1095
voltage duty ... 1116
wireless set test ... 1110
porcelain, design, requirements to be observed ... 1193
suspension, acceptance vs. service durability. 1438
bibliography ... 1450
cementing pin, effect ... 1440
detecting porosity ... 1442
durability ... 1437

Insulators, porcelain, suspension (*continued*)

- experiments on, 1453
  - corona discharge, guarding against, 1456
  - high-voltage megger, 1455
  - moisture effects, 1461
  - pull-resistance studies, 1458
  - scope of, 1454
  - temperature resistance studies, 1459
  - voltage resistance studies, 1458
  - water-logging, 1461
- fireclay, relative porosity, 1447
- fundamental requirements, 1437
- over- and under-firing, 1441
- porosity curves, North Carolina Kaolin and English China Clay, 1446
    - Tennessee Ball Clay, 1445
    - various composition, 1444
  - effect of materials in solution, 1439
  - trial by gaseous conduction, 1443
- resistivity-temperature curves, 1449
- wet process, advantages and disadvantages, 1448
  - vs. dry process, 1440
- testing, concentrated resistance, 741
  - dielectric losses, 734
  - distributed internal resistance, 739
  - oscillator, 743
  - surface leakage, 741
- porous vs. non-porous, 1199
- resistance recorder, 712
- suspension, deterioration investigation, 1467
  - graded, voltage distribution curves, 751
  - grading, measurement of distribution of voltage, 747
    - methods adopted, 747
    - new method, 745
    - theory, 746
  - meggering, kenetron, use, 1468
  - metallic attachments, effect on stress, 1469
  - moisture absorption, rate, 1470
  - surface spark-over, 790
  - testing, laboratory method, 737
    - megger and others, 735
      - method, cost, 736
  - ungraded, voltage distribution curves, 750

Interference, inductive (See Inductive interference, etc.)

- use of arcing ground suppressor, 720

Inventories, continuous, preparation, 1379

- and value, 1375
- forms, 1382 to 1386
- grouping property, 1381

Inventories, continuous, preparation (*continued*)
work orders ... 1380
value and use ... 1375
Inventory and appraisal "appreciation value" ... 1424
classification as to use ... 1372
going value ... 1374
preparation, change sheets, value of ... 1408
"present worth" ... 1426
"property growth" ... 1428
property used and useful ... 1371
recent decisions, effect of ... 1369
reproduction value vs. original value ... 1370
true valuation factors ... 1373
value new vs. depreciated value ... 1371
value not cost ... 1370
Iron losses, d-c. machines ... 261
armature ring, full load ... 281
losses ... 267
tooth loss, full load ... 282
no load ... 268
calculation, equation for increased air gap, no load ... 275
classification of core losses ... 262
commutating and non-commutating pole 287
compensating winding, disadvantages. 296 298
eddy current losses, divided conductors. 291
effect of frequency ... 295
eddy currents in copper, full load ... 283
effect of filing and of pressure, armature core ... 265
effect of high copper loss on core loss, curve ... 271
effect of open slots on flux density, no-load ... 276
effect of shearing, punching and bending armature core ... 264
laminations, effect of excessive pressure ... 294
pole face losses, determination by special homopolar generator. 297
full load ... 284
due to armature slots, equation, no-load ... 277
stray losses, full load ... 284
no-load ... 278
tufting or bunching of flux, pole face ... 267
variables to be considered ... 263
railway motors ... 289
transformers ... 288
J. G. White Engineering Corporation, report on grounded neutral ... 581
Lighting, Panama-Pacific International Exposition (See Illumination, P. I. E.)
power rates ... 989
Lightning arresters, point of connection ... 1197 1200
frequency of discharge ... 877
protection, 4000-volt circuit (See Protection, lightning, etc.)
of transmission lines, parallel grounded wires (See Wires, parallel grounded, etc.)
studies in protection, 4000-volt circuits, Chicago ... 655
Liquid rheostat, mine service, diagram ... 172
Norfolk and Western Railway ... 167
railway service, construction ... 167

- Liquid rheostat, railway service (*continued*)
  - cooling tower 171 172
    - capacity 173
  - functions 167
  - horizontal arrangement of tanks 170
  - schematic connection diagram 168
  - section diagram 169
- Macadam road, tractive resistance, motor truck 944
- Machinery, electric, specifications, modern standards (See Specifications, electric machinery, etc.)
- Measuring instruments, research subjects 907
- Megger, test, insulators, defective 1097
  - tests, suspension insulators (See Insulators, suspension, testing, etc.)
- Motor truck, tractive resistances, different roads and speeds (See Tractive resistances, trucks, etc.)
- Motors, d-c., reversing rolling mill drive (See Rolling mills, reversing, etc.)
  - induction, protection, after service interruptions 640
  - oil wells 539
    - a-c. vs. d-c. equipment 540
    - all operations, total power consumption curve 544
    - convenience 553
    - drilling 540
      - wiring diagram 545
      - and bailing, power curve 543
    - elevation and plan of equipment 541
    - lifting tubing, h.p. required, formula 548
    - mechanical efficiency of rig, approximate 549
    - pumping, pulling and cleaning 546
    - "spudding in" casing, power curve 542
    - two-motor equipments 552
    - two-speed type, diagram of connections 551
    - Y-delta and two-speed types 550
  - research subjects 902
  - rolling mill drive, reversing (See Rolling mills, reversing, etc.)
  - synchronous, protection, after service interruption 641
- Mt. Whitney Power & Elec. Co., report on grounded neutral 577
- Multi-recorder, use by Public Service Electric Co. 712
- N. Y., N. H. & H., single-phase problem 1295
- Nitrogen, fixation (See Water power development, etc.)
- Non-grounded neutral system, isolating transformers 717
- Norfolk & Western, operation 147
- Oil circuit breakers, rupturing capacities (See Circuit breakers, oil, etc.)
  - effect of high continuous voltages 783
  - spark-over voltages, needle gaps 791
  - wells, motor equipment (See Motors, oil wells, etc.)
- Oscillation transformer, testing for defective insulators 1096
- Oscillator testing, porcelain insulators 743
- Oscillograph, Bennet, small current 1132
- Pacific Light & Power Co., report on grounded neutral 571
  - transmission lines, plan 572, 574 575
- Panama-Pacific International Exposition, illumination 757
- Penn. Water & Power Co., grounded neutral report 561
- Phenomena, a-c., calculation of, polar form complex quantities 957
- Phonographic alphabet, writing machine 213
- Porcelain, insulators, breakdown, transient voltages 1187
    - suspension, durability (See Insulators, porcelain suspension, etc.)
  - suspension insulators, experiments on (See Insulators, porcelain suspension, etc.)
  - testing (See Insulators, porcelain, testing, etc.)

- Porosity, porcelain insulators, testing 739
- Potential, electrostatic, indicating devices 715
- Potentiometer, high-voltage 1131
- Power, calculation, polar form of complex quantities 963
  - consumption of, electrochemical industries 387
  - cost, Niagara 387
  - domestic, distribution system, commercial and engineering standpoints 983
  - hydroelectric, development, electrochemical possibilities 260
    - future development methods 259
    - possible development in U. S., estimated 256
  - installed, hydroelectric, development 253
    - distribution of development 254
    - geographical distribution 252
    - proportion of central-station power 255
  - plants, design and economics, research subjects 905
  - primary, total fixed installed, U. S. 249
    - percentage hydroelectric 251
  - single-phase, advantages of large capacity unit 1308
    - balancer vs. single-phase motor, cost 1305
    - balancers, essential requirements 1341
    - balancing a 3-phase generator, methods 1291
    - capacity diversity 1304
    - central station generation 1329
      - separate generators 1332
      - supply 1293
    - cost at Niagara 1307
      - factor 1317
      - of apparatus, various methods of generation 1348 1357
    - customer power factor correction 1350
    - direct from polyphase system 1330
      - auxiliary balancers 1336
      - single-phase booster 1337
      - unbalanced feeder e.m.f.'s 1340
    - equipment for mixed polyphase and single-phase load 1325
    - equipment for mixed polyphase and single-phase load, diagrams of connections 1326
    - fluctuating type 1309
    - generator theory 1332
    - limiting capacity of generators 1358
    - load factor 1290
    - methods of production 1316
    - N. Y., N.H.& H., Cos Cob station, unbalancing figures 1303
      - map of supply lines 1296
      - methods of supply considered 1297
      - problems 1295
      - 201st St. station, diagram of connections 1298
      - West Farms substation, diagram of connections 1299
    - phase balancer, limiting the load 1356
    - phase converter, applications 1323
      - considered as motor-generator 1319
      - considered as a polyphase generator 1320

- Power, single-phase, phase converter (*continued*)
    - considered as a transformer 1321
    - current relations 1352
    - explanation of action 1352
    - theory of 1318
  - power company's problem 1289
  - power factor 1306
    - correction 1292
    - generators designed for less than unity 1309
    - regulation 1356
  - production 1315
  - railway, supply from 3-phase generators 1295
  - relative size of generators 1349
  - several distributing substations 1294
  - synchronous condenser, justification of 1351
  - three-phase generator with dampers, efficiency 1366
  - various methods of generation, comparative efficiency 1348
  - voltage triangles, polyphase generator, balanced and unbalanced 1331
  - steam locomotive generated, U. S., estimated 250
- President Carty's Address (Relation of Pure Science to Industrial Research) 479
- Protection, high-voltage systems, isolating transformers 717
  - lightning, 4000-volt circuit 655
    - behavior of arresters 690
    - Chicago investigation, data on transformers 666
    - Chicago investigation, data on transformers burned out in 1915....668, 669 670
    - Chicago investigation, location of burned out transformers, 1915 671
    - Chicago investigation, transformer troubles according to size.......679 680
    - Chicago investigation, transformers, relation of terminal boards to fuses blown 682
    - determining effectiveness of arresters 659
    - examination of transformers for arcing 657
    - extra large transformer primary fuses 662
    - grounding transformer cases 661
    - location of arresters on transformer poles 658
  - service (See Service, restoration, etc.)
    - individual differential or balance method 724
    - Public Service Electric Co., air washer 713
      - aluminum cell arresters 699
      - arcing ground suppressor 699
      - cable testing 700
      - coherer alarm device 714
      - dampers for air-blast transformers 714

Protection, service, Public Service Electric Co. (*continued*)
- exciter connection scheme........ 703
- experience....... 695
- faulty cable localizer........... 700
- generator bus scheme........ 701
- high-potential and high-frequency tests.......... 701
- insulation resistance recorder.. 712
- multi-recorder.... 712
- potential indicating devices.... 715
- reactors......... 703
- relays........... 707
- resistance bulbs and thermocouples....... 713
- troubles encountered.......... 698
- split-conductor principle.................. 724

Public Service Electric Co., plan transmission system........... 570
- protective features, diagram of transmission system.......696 697
  - experience....... 695
- report on grounded neutral.......... 569
- utilities, municipal, basis of criticism.................... 33
  - Canadian, central heating systems..... 82
    - character of service........ 83
    - characteristics of cities..... 35
    - charges for municipal lighting and railway power.... 64
    - classes of service furnished.. 58
    - cost and financing......... 50
    - cost per kw-hr., table...... 53
    - data on cities, Calgary..... 41
      - Edmonton... 40
      - Medicine Hat and Lethbridge 39
      - Moose Jaw.. 38
      - Regina and Saskatoon. 37
      - Winnipeg and Kamloops...... 42
    - debentures issues and sinking funds.............. 59
    - depreciation and obsolescence................ 63
    - disposal of surplus......... 16
    - distribution systems....... 50
    - extravagant investments... 93
    - financial statements, tabular summary........... 52
    - monthly lighting charges, large consumers......... 71
    - monthly lighting charges, small consumers......... 70

Public utilities, municipal, Canadian (*continued*)
monthly power charges, large consumers 73
monthly power charges, small consumers 72
Moose Jaw, demand growth, curve 57
organization 43
principles of 85
plant operation, general data 69
power plants and equipment 46
revenue disposition 97
social considerations 34
steam plant equipment, table 47
taxation 57
unfair competition 94
value of public service commission 84
western 33
charges to other departments 92
financing, question of length of life of project 88
obsolescence 91
range of service 90
taxation 89
Puget Sound Traction, Light & Power Co., report on grounded neutral 579
Pure science, relation to industrial research (President Carty's Address) 479
Radio transmission, research subjects 908
Railroad, electric, d-c. vs. single-phase vs. three-phase 160
Milwaukee & St. Paul, braking 154
regenerative braking 155
Norfolk & Western, absorbing rheostat for regenerative power 166
approximate profile 148
disadvantage under steam service 149
effect of voltage variation 161
increased service due to electrification 150
liquid rheostat (See Liquid rheostat, Norfolk & Western, etc.)
locomotives, braking 152 156
control 152
power handled, various conditions 157
map 148
method of starting 151
variation in wheel diameter, compensation for 156
water rheostats 156 158
operation, advantage, Norfolk & Western 147
three-phase motors, constant speed advantages 165
Railways, d-c., 2400 and 3000 volts 357
5000-volt 359
description 375
high-voltage 347
Budapest City Railroad 369

- Railways, d-c., high-voltage (*continued*)
  - Chicago, Milwaukee & St. Paul, collection system 366
  - control 349
    - alternatives offered 353
    - auxiliary devices 350
    - drum 354
    - operation on two voltages 351
  - early predictions 361
  - line construction 356
  - locomotive cost vs. copper cost 365
  - motors 348
  - power supply 254
  - switching 355
  - ultimate limits 358
  - voltage determining factors, locomotive cost 364
- Rand Mines Power Supply Co., Ltd., report on grounded neutral 590
- Rates, domestic power 989
  - advantage of single-meter system 994
  - off-peak requirements, disadvantages 998
  - light and power, municipal utilities, Canadian (See Public utilities, municipal, etc.)
- Rating, circuit breakers, oil (See Circuit breakers, oil, rating, etc.)
- Reactance, selector 725
- Reactors, Public Service Electric Co. 703
- Relays, balanced selective, use by Public Service Electric Co. 710
  - definite-time-limit overload 597
  - differential 596
  - inverse-time-limit overload 597
  - reverse-current 597
  - use by Public Service Electric Co. 707
- Research, electrical, engineering colleges, suggestions 895
  - list of subjects 902
- Resistance bulbs, use by Public Service Electric Co. 713
  - distributor, water 1132
- Resistances, tractive, motor truck, different roads and speeds (See Tractive resistances, truck, etc.)
- Rolling mills, reversing, electric drive 501
  - comparison with mine hoist drive 521
  - economy of operation 533
  - European vs. American practise 528
  - excitation 530
  - first cost 532
  - forced ventilation 534
  - generators 529
  - insulation of machines 519
  - list of installations 531
  - relation watt-hours to elongation 508
  - schematic diagram 503
  - series exciter 504
  - shaft strength 522
  - Steel Co. of Canada, installation and operating costs 523
  - summary of advantages 524
  - time study 511 512
  - voltage selection 513
  - windings for generators 516
  - electric vs. steam drive 505
    - comparative costs 506

- Rolling mills, reversing (*continued*)
  - steam drive, steam consumption ... 507
    - 5000-k w. turbine 509
    - vs. electric drive, boiler capacity factor ... 520
    - speed curves ... 510
- Selenium cell ... 235
- Service, restoration, a-c. distribution feeders, diagram of relay connections ... 645
  - oscillograms of 6600-volt system operation ... 647
  - after necessary interruption ... 635
    - generator protection ... 636
    - induction motor protection ... 640
    - synchronous converter protection ... 640
    - synchronous motor protection .. 641
  - generator protection, relays ... 636
  - voltmeter charts showing effect of lightning strokes ... 644
- Single-phase power, power company's problem (See Power, single-phase, etc.)
  - production ... 1315
- Slip, chattering wheel, electric motive power (See Wheel slip, etc.)
- Sparking probe ... 1132
- Spark-over voltages, air, etc. (See Air, spark-over voltages, etc.)
  - oil (See Oil, spark-over voltages, etc.)
- Specifications, electrical machinery, ambient temperature, acceptance tests ... 1264
  - ambient temperature of reference ... 1261
  - insulation, intensified aging .. 1274
  - loss per degree air rise ... 1282
  - loss per degree air rise, embedded detectors ... 1283
  - maximum shade temperatures, various locations ... 1263
  - open-circuit and short-circuit losses, 3-phase, 12-pole alternator ... 1281
  - room-temperature, effect on temperature rise ... 1266
  - temperature, circulating air .. 1276
    - limits, comparison, British and American Rules ... 1286 1287
    - rise, correction factors ... 1267
    - rise, embedded detectors ... 1267
    - rise, equivalent tests ... 1278
    - rise, hottest spot 1268
    - rise, hottest-spot temperature .. 1272

- Specifications, electrical machinery, temperature (*continued*)
  - rise, initial temperature of winding...... 1270
  - rise, location of detectors.. .. 1269
  - rise, margin of safety....... 1277
  - rise, overload rating....... 1275
  - temperature-time curves..... 1284
  - tests, modern standards...... 1259
- Speech, true nature.......... 213
  - brain cell analogy to Baudot system of telegraphy.......... 234
  - comparison of English, phonographic and submarine cable alphabet, table.......... 227
  - definition.......... 213
  - harmonic vs. absolute pitch theory........ 243
  - Helmholtz formula, resonance spherical cavity.......... 226
  - natural alphabet, pattern forms.......... 219
  - phonographic alphabet writing machine, operation.......... 230
  - phonographic alphabet writing machine wiring diagram and arrangement.......... 228
  - phonographic records, approximations....... 236
  - selenium cell.......... 235
  - speech and voice, distinction.......... 216
  - string galvanometer, motion equation....... 237
  - vowels and consonants, definition.......... 215
  - whispered speech, acousticon transmitter.... 217
    - pattern pictures.......... 218
  - written and spoken language.......... 216
- Standardization, national and international.......... 489
- Steel conductors, transmission lines (See Transmission, conductors, steel, etc.)
- Stefan-Boltzman law, heat radiation.......... 601
- Surges, electrical measurement of.......... 107
- Switches, sequence of action, multi-recorder.......... 712
- Telephone receiver test, defective insulator.......... 1097
- Temperature, ambient.......... 1261
  - distribution, armature, equalization of temperature. 1480
    - heat flow through iron...... 1477
      - to air........ 1478
    - many conductor coils....... 1486
    - coil.......... 1473
      - lateral heat flow........ 1475
      - locating thermo-couples. 1476
      - longitudinal heat flow... 1473
  - electrical machinery.......... 1471
    - heat flow rules.... 1471
  - guarantees, a-c. generators, armature current vs. field current 1498
    - rise vs. load... 1492
    - heat flow calculations.. 1495
    - inconsistent guarantees. 1491
    - low rise, advantage.... 1492
    - permissible rises....... 1490
    - rotor, rise vs. volts drop. 1497
    - thermal drop formula.. 1496
  - exciting current limit.......... 1520
  - fallacies.......... 1481

Temperature, guarantees (*continued*)
generators, a-c. 1489
mica insulation, importance of firm binding 1517
relative conductivities 1494
turbo-generators, amount of ventilating air passed 1519
measurement, eddy currents, effect of 1504
errors 1482
periodic generators 1514
resistance coils, disadvantages 1484
location 1485
thermocouple 1486
location, errors 1506
transformers 1508
operating, effect of altitude 555
radiation, conduction and convection laws 600
induction apparatus 599
barometric pressure on radiation, conduction and convection 608
room temperature on radiation, conduction and convection 607 608
stationary induction apparatus, theoretical calculation 611
rise, air-flow effect 1510
cables, insulated lead-covered (See Cables, temperature rise, etc.)
Class A and Class B insulations, relations curve 1515
generators, air washer 713
insulation thickness, limiting value 1513
limit, determination of 1511
The Colorado Power Co., report on grounded neutral 579
The Montana Power Co., report on grounded neutral 579
The Toronto Power Co., report on grounded neutral 578
Thermal capacity, watt-hr. per inch cube; copper, iron, steel, lead, rubber, paper 1031
conductivity, cables 1019
Thermocouples, used by Public Service Electric Co 713
Traction, electric, research subjects 905
Tractive resistances, truck, battery specifications 930
brick-block road 943
cinder and gravel road 946
different roads and speeds 925
elevations and cross-sections 927
experimental procedure 931
granite-block road 943
laboratory tests 933
level asphalt road, curves 941
macadam road 944
motor and controller specifications 929
overall efficiency of driving mechanism 935
specifications of motor truck 926
wood-block road 942
Transformer, iron losses, eddy current losses 290
testing, variation of crest factor 101
wave form 101
Transformers, air-blast, dampers 714
iron losses 288
isolating, high-voltage systems (See Protection, high-voltage systems, etc.)
lightning protection (See Protection, lightning, etc.)
research subjects 904

Transformers (*continued*)
temperature guarantees........................ 1508
rise, calculation (See Temperature, operating, stationary induction apparatus, etc.)
rise effect of altitude, formulas recommended..... 625
general equation......... 614
test on 125-kw., 11000-2300 volt transformer.......... 629
Transient voltages, insulator failures (See Insulators, transient voltages, etc.)
Transmission Committee Report, "Effect of Altitude on Operating Temperature"............ 555
"Experience with Grounded Neutral on High-Tension Transmission Lines"....... 560
conductors, steel.................................. 1237
100,000-volt lines................ 1247
a-c. vs. d-c...................... 1238
branch lines...................... 1245
copper clad....................... 1253
corona limit values............... 1258
cost relative to copper........1246 1257
damping of surges................ 1243
examples.......................... 1248
internal reactance curves........ 1243
length of spans.................. 1244
resistance curves..........1239 to 1242
scrap value and corrosion........ 1252
spiraling, effect on magnetization...................1242 1244
steel-copper joints............... 1256
trolley wires..................... 1251
d-c., high-tension, advantages.................... 802
high-tension, defective insulators, testing for (See Insulators, high-tension, defective, etc.)
grounded neutral, advantages of generating station ground............ 592
grounded neutral, Alabama Power Co 581
Chicago & Interurban Traction Co............ 580
experiences....... 560
J. G. White Engineering Corporation........... 581
metallic grid vs. water resistance.. 593
Mt. Whitney Power & Elec. Co...... 577
Pacific Light & Power Co....... 571
Penn. Water & Power Co....... 561
Penn. Water & Power Co., groundcurrent oscillograms....... 565

Transmission, high-tension, grounded neutral (*continued*)
Penn. Water & Power Co., resistance and reactance tables.... 567 568
Penn. Water & Power Co., single-wire grounds 566
Public Service Electric Co.......... 569
Puget Sound Traction, Light & Power Co....... 579
The Colorado Power Co.......... 579
The Montana Power Co.......... 579
Toronto Power Co. 578
Utah Power & Light Co....... 579
Victoria Falls & Transvaal Power Co., Ltd........ 590
quarter-wave oscillations............ 22
transient voltages, insulator failures.. 1187
origin............ 1188
research subjects............................ 905
line, artificial, adjustable constants.............. 1137
costs........... 1141
bibliography.................. 1149
condensance element.................. 1140
distributed and lumpy types........ 1150
experiments, resonance............ 1145
sudden impressed impulses............ 1142
voltage and current along line........... 1143
inductance element............... 1140
instruments........................ 1141
resistance element............... 1109
wiring diagram.................. 1138
parallel grounded wires, theory and use (See Wires, parallel grounded, etc.)
poles, protection against lightning, grounded vertical wire........................... 849
Transportation problem vs. water power development (See Water power development, etc.)
United Electric Light & Power Co., 201st St. Station, N. Y., N. H. & H. supply, diagram of connections....... 1298
West Farms substation, N. Y., N. H. & H. supply, diagram of connections.... 1299
Utah Power & Light Co., report on grounded neutral........... 579
Underground distribution systems (See Distribution, underground, etc.)
Ventilation, turbo-generators, amount of air passed............. 1519
Victoria Falls and Transvaal Power Co., Ltd. report on grounded neutral.. 590
Voltage, high, measurement.................................. 119
cathode ray cyclograph............. 141
connections for a 300-kw. 300,000 volt test........................... 144

Voltage, high, measurement (*continued*)
- corona method 136
- crest voltmeter method, errors introduced 125
- determination of crest factors 121
- diagram of connections 120
- electrostatic vs. oscillograph 132
- experimental apparatus 119
- impulse transformer method 130
- methods 127
- necessity for satisfactory standard 139
- secondary and tertiary voltages 122
- secondary voltage by crest voltmeter 124
- sphere gap method 128

rises, coherer alarm device 714

Voltmeter coil, testing transformers 117
- testing accuracy 143

corona 809
- 50,000-volt type 818
- 100,000-volt type 815
- calibration 822
  - permanence 829
- comparison with sphere gap readings 842
- dimensions 831
- ionization, effect 841
- method of measurement 827
- pressure type 838
  - vs. temperature, table of values 828

crest 99 109
- accuracy 113
- advantages 115
  - over needle and sphere spark gaps 110
- applications 115
- calibration 113
- construction 111
- desirable characteristics 109
- diagram of connections 103 111
- electrostatic type 133
  - construction 134
- galvanometer deflections vs. crest voltages, proportionality 105
- historical 110
- necessity of 99
- operation 112
- possibility of measuring surges 107
- rotating vs. hot cathode rectifiers 114
- testing, built-up waves, diagram 104
  - transformer, variation of crest factor 101
    - wave form 101
      - distortion 100

Washington Water Power Co., protection features 1195

Water heating, electric 1008
- high power factor heater, description 1012
- rates 1009
- wiring diagram of range 1009

power, future in U. S. 249
- development, electrochemical industries, interest of (See Electrochemical industries, etc.)
- development, electrochemical industries, freight rates vs. power costs 421
- development, electrochemical industries, part time operation 459

Water power, development (*continued*)
- financial aspect 441
  - combination of various sources of power .. 446
  - effect of laws and precedents 445
  - excessive promoter charges 462
  - installation, initial ultimate capacity 447
- food problem 393
  - agricultural aspect 396
  - fertilizer distribution in 1909 401
  - harvest statistics 400
  - importation of fertilizer. 398
  - manufacture of fertilizers 397
  - potash and phosphate extraction 399
- nitrogen, fixation, Cyanamid process. 438
  - du Pont process ... 438
  - utilization of present electric installations 436
- possible nitrogen sources, coking industry 466
- transportation problem 403
- transportation problem, canal vs. railroad construction, cost 414
- transportation problem, construction of dams 409
- transportation problem, permissible hydroelectric investment 411
- transportation problem, permissible hydroelectric investment stand-by steam plant 412
- transportation problem, railroad fuel cost vs. total operating expense 406
- transportation problem, railroad operating expenses 404
- transportation problem, steam locomotive vs. electric power 427
- transportation problem, steam power cost, recent improvement 408 423
- transportation problem, steam vs. electricity, average cost 405
- vs. defense 431
  - nitrate importation 432

Wattmeter, polyphase, connections, checking 183 192
- by opening supply .. 203
- classification 184
- effect of unbalanced load 208
- equation verification 190
- possible arrangements 185
- rate of rotation, equations ... 187
- two wattmeter check 210
- with voltage transformers 197

Wave form, deviation factor 1156
- standard, admittance type 1155
  - inductive interference, committee report ... 1171

Wheel slip, chattering, characteristic diagram 178
- cure 180
- electric motive power 175

ol. 35
916

Wheel slip, chattering (*continued*)
    recording device........................ 177
    use of extensometer...................... 178
Wires, overhead, induced charges, movements.................. 875
    grounded, analysis of uses.................... 848
        arrangement....................... 882
        calculations of protection afforded.... 854
        charge induced on single wire, effect of height........................ 855
        charge induced on single wire, effect of size.......................... 857
        cost................................ 883
        general problems of the parallel wire... 851
        instantaneous induced potential, laws. 860
        oscillating surges.................. 871
        protection, two-parallel............. 868
            vertical arrangement..... 865
            and potential ratios, equations................ 885
        protective effect to parallel circuits.... 889
        screening effect.................... 863
            one parallel wire...... 864
        self-inductance, - natural frequency, critical resistance, etc............. 871
        theory and use..................... 845
        transposition, high frequency effect... 878
        travelling waves, absorption of....... 876
    ungrounded, induced charge.................. 858
        screening of energy by several wires 861
Wood-block roads, tractive resistances, motor truck............ 942

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OUTLINE OF THEORY OF IMPULSE CURRENTS

BY CHARLES P. STEINMETZ

Abstract of Paper

In Part I it is shown how, from the integral of the general differential equation of the electric circuit, which has been discussed in a previous paper, all the types of electric currents are derived as special cases, corresponding to particular values of the integration constants.

The equations of the circuits with massed constants, that is, the usual electric circuits, are derived by substituting zero for the (electrical) length of the circuit.

Besides the general transients, discussed in a previous paper, three main classes of currents are shown to exist, corresponding to different values of the time exponent b:

The alternating currents, corresponding to b = imaginary, which are the useful currents of our electric circuits.

The impulse currents, corresponding to real values of b, which may be called harmful currents of our electric circuits.

And, as limit case, for $b = 0$, the continuous-current circuit with distributed constants.

The last case, a continuous current in a circuit with distributed resistance and leakage, is discussed, and it is shown that such continuous-current circuit has many features which are usually considered as typical of alternating-current wave transmission. It consists of a main current and a return current; complete reflection occurs at the end of the circuit; partial reflection at a transition point; a surge resistance exists, which, connected to the circuit, passes the current without reflection.

In Part II an outline of the theory of impulse currents is given. They comprise two classes, the non-periodic and the periodic impulse currents. The equations of both are given in different form, by exponential and by hyperbolic or trigonometric functions. Their characteristics are:

Impulse current and voltage may be resolved into a main wave and a return wave. The return wave is displaced from the main wave in time and in position. A time displacement exists between the two current waves and their corresponding voltage waves. This time displacement may be a lag of the current behind the voltage, or a lead, depending on the circuit constants. In the periodic impulse currents, the displacement between main wave and return wave is represented by a position angle, and the two current waves are in quadrature in position, to their respective voltage waves.

A few special cases are discussed.

I. TYPES OF CURRENT

A. General

IF

r = resistance
g = shunted conductance
L = inductance
C = capacity

per unit length of any circuit or section of a circuit, then in any line element *dl* of the circuit, the voltage consumed is

$$\frac{d\,e}{d\,l} = ri + L\,\frac{di}{dt} \tag{1}$$

and the current consumed is

$$\frac{d\,i}{d\,l} = g\,e + C\,\frac{d\,e}{d\,t} \tag{2}$$

Differentiating (1) over *dt*, and (2) over *dl*, and combining gives

$$\frac{d^2i}{dl^2} = LC\,\frac{d^2i}{dt^2} + (r\,C + g\,L)\,\frac{d\,i}{d\,t} + r\,g\,i \tag{3}$$

Integrating,

$$i = A\,\epsilon^{-al}\,\epsilon^{-bt} \tag{4}$$

$$e = \frac{b\,L - r}{a}\,A\,\epsilon^{-al}\,\epsilon^{-bt} \tag{5}$$

$$= \sqrt{\frac{b\,L - r}{b\,C - g}}\,A\,\epsilon^{-al}\,\epsilon^{-bt}$$

$$= z\,i$$

where

$$z = \sqrt{\frac{b\,L - r}{b\,C - g}} \tag{6}$$

is the *surge impedance* or *natural impedance* of the circuit, and a and b are related by the equation

$$a^2 = b^2 LC - b\,(rC + gL) + rg \tag{7}$$

$$= (bL - r)\,(bC - g)$$

The general solution then is a sum of such terms (**4**) and (**5**).

These equations must represent every existing electric circuit, and every circuit which can be imagined, from the lightning discharge to the house bell, and from the alternating-current transmission line to the telephone circuit, with the only limitation, that r, g, L, C are constant within the range of the currents and voltages considered.

The difference between all electric circuits thus merely consists in the difference of the constants A, a and b, and the difference in the length l of the circuit.

If $l = 0$, that is, the length of the circuit is negligible compared with the rate of change of i or e, (**4**) and (**5**) give the equations of all the circuits with massed constants, otherwise we get the equations of the circuits with distributed constants.

In general, a and b are general numbers, related to each other as in (**7**). Choosing b as the independent constant,

$b = 0$ gives the continuous currents.
$b =$ real gives the impulse currents.
$b =$ imaginary gives the alternating currents.
$b =$ general or complex imaginary gives the general transients.
$b = 0$ or imaginary thus gives the *permanents*, continuous current and alternating current.
$b =$ real or general gives the *transients*, impulse currents and general transients.

Thus, while the continuous currents represent a limiting case, the alternating currents and the impulse currents are two coordinate classes of currents. While the alternating currents are the useful currents of our electric systems, the impulse currents may be said to be the harmful currents in our systems, as many of the disturbances and troubles in electric systems are caused by them.

The theory of alternating currents is discussed in numerous publications, but little systematic study has been made of the impulse currents, and their general theory thus will be given in the following, and also that of the limiting case of the continuous currents in a general circuit of distributed constants. The theory of the general transients has been outlined in a previous paper.*

B. CIRCUITS WITH MASSED CONSTANTS

Substituting in (**4**) and (**5**):

$$e = 0 \text{ when } l = 0$$

and considering that, by equation (**7**), a can have two values, for every value of b, $+ a$ and $- a$, we have,

$$i = A\,\epsilon^{-bt}\,\{\epsilon^{-al} + \epsilon^{+al}\}$$

$$e = \frac{bL - r}{a}\,A\,\epsilon^{-bt}\,\{\epsilon^{-al} - \epsilon^{+al}\} \qquad (\mathbf{8})$$

Assuming now l as infinitely small, and substituting

$$\epsilon^{\pm al} = 1 \pm a\,l \qquad (\mathbf{9})$$

in (**8**), gives, as the general equation of the circuit with massed constants,

$$i = B\,\epsilon^{-bt}$$

$$e = (r_0 - bL_0)\,B\,\epsilon^{-bt} \qquad (\mathbf{10})$$

where

$B = 2\,A$

$r_0 = l\,r =$ total resistance of circuit,

$L_0 = l\,L =$ total inductance of circuit.

Substituting $b = 0$ in (**10**), gives

$$i = B$$

$$e = r_0\,B \qquad (\mathbf{11})$$

as the equation of the continuous-current circuit.

For $b =$ real (**10**), the equations of the inductive discharges are

$$i = B\,\epsilon^{-bt}$$

$$e = (r_0 - bL_0)\,B\,\epsilon^{-bt}$$

$$= r_0\,i + L_0\,\frac{di}{dt} \qquad (\mathbf{12})$$

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*A. I. E. E. TRANSACTIONS 1908, page 1231, and more completely in Section IV of "Transient Phenomena."

Substituting $b = \pm j\, c$ gives as the equation of the alternating-current circuit,

$$\begin{aligned} i &= C_1 \cos ct + C_2 \sin ct \\ e &= (r_0 C_1 - c L_0 C_2) \cos ct + (r_0 C_2 + c l_0 C_1) \sin ct \end{aligned} \tag{13}$$

where

$$\begin{aligned} C_1 &= B_1 + B_2 \\ C_2 &= j\,(B_1 - B_2) \end{aligned} \tag{14}$$

C. CONTINUOUS-CURRENT CIRCUIT WITH DISTRIBUTED CONSTANTS

$$b = 0$$

From (7) we have

$$a = \pm \sqrt{rg} \tag{15}$$

and from (6),

$$z = \pm \sqrt{\frac{r}{g}} \tag{16}$$

substituting (15) and (16) in (4) and (5) gives

$$i = A_1\, \epsilon^{-l\sqrt{rg}} + A_2\, \epsilon^{+l\sqrt{rg}} \tag{17}$$

$$e = \sqrt{\frac{r}{g}}\, \{A_1\, \epsilon^{-l\sqrt{rg}} - A_2\, \epsilon^{+l\sqrt{rg}}\} \tag{18}$$

These equations do not contain L and C, that is, inductance and capacity have no effect on the permanent continuous-current circuit with distributed constants, but only resistance and conductance, that is, leakage.

Equations (17) and (18) are the equations of a direct-current circuit having distributed leakage, such as a metallic conductor submerged in water, or the current flow in the armor of a cable laid in the ground, or the current flow in the rail return of the direct-current railway, etc.

r is the series resistance per unit length, g the shunted or leakage conductance per unit length of circuit.

Where the leakage conductance is not uniformly distributed, but varies, the numerical values in (**18**) change wherever the circuit constants change, just as would be the case if the resistance r of the conductor changed. If the leakage conductance g is not uniformly distributed, but localized periodically in space —as at the ties of the railroad track,—when dealing with a sufficient circuit length, the assumption of uniformity would be justified as an approximation.

(*a*) If the conductor is of infinite length—that is, of such great length, that the current which reaches the end of the conductor, is negligible compared with the current entering the conductor, we have

$$A_2 = 0$$

This gives

$$\left.\begin{aligned} i &= A\,\epsilon^{-l\sqrt{rg}} \\ e &= A\sqrt{\frac{r}{g}}\,\epsilon^{-l\sqrt{rg}} \end{aligned}\right\} \qquad (\mathbf{19})$$

or

$$e = \sqrt{\frac{r}{g}}\,i \qquad (\mathbf{20})$$

that is, a conductor of infinite length (or very great length) of series resistance r and shunted conductance g, has the effective resistance $r' = \sqrt{\frac{r}{g}}$.

It is interesting to note, that at a change of r or of g the effective resistance r', and thus the current flowing into the conductor at constant impressed voltage, or the voltage consumed at constant current, changes much less than r or g.

(*b*) If the circuit is open at $l = l_0$, we have

$$i = A_1\,\epsilon^{-l_0\sqrt{rg}} + A_2\,\epsilon^{+l_0\sqrt{rg}} = 0$$

Hence, if

$$A = A_1\,\epsilon^{-l_0\sqrt{rg}} = -A_2\,\epsilon^{+l_0\sqrt{rg}}$$

we have

$$\left.\begin{aligned} i &= A\left\{\epsilon^{+(l_0-l)\sqrt{rg}} - \epsilon^{-(l_0-l)\sqrt{rg}}\right\} \\ e &= A\sqrt{\frac{r}{g}}\left\{\epsilon^{+(l_0-l)\sqrt{rg}} + \epsilon^{-(l_0-l)\sqrt{rg}}\right\} \end{aligned}\right\} \qquad (\mathbf{21})$$

(*c*) If the circuit is closed upon itself at $l = l_0$, we have

$$e = \sqrt{\frac{r}{g}}\,\{A_1\,\epsilon^{-l_0\sqrt{rg}} - A_2\,\epsilon^{+l_0\sqrt{rg}}\} = 0$$

Hence, if

$$A = A_1\,\epsilon^{-l_0\sqrt{rg}} = A_2\,\epsilon^{+l_0\sqrt{rg}}$$

we have

$$\begin{aligned} i &= A\,\{\epsilon^{+(l_0-l)\sqrt{rg}} + \epsilon^{-(l_0-l)\sqrt{rg}}\} \\ e &= A\sqrt{\frac{r}{g}}\,\{\epsilon^{+(l_0-l)\sqrt{rg}} - \epsilon^{-(l_0-l)\sqrt{rg}}\} \end{aligned} \qquad (22)$$

If, in (**22**), $l_0 = 0$, that is, the circuit is closed at the starting point, we have

$$i = A\,\{\epsilon^{-l\sqrt{rg}} + \epsilon^{+l\sqrt{rg}}\}$$

$$e = A\sqrt{\frac{r}{g}}\,\{\epsilon^{-l\sqrt{rg}} - \epsilon^{+l\sqrt{rg}}\}$$

or, counting the distance in opposite direction, that is, changing the sign of l

$$\begin{aligned} i &= A\,\{\epsilon^{+l\sqrt{rg}} + \epsilon^{-l\sqrt{rg}}\} \\ e &= A\sqrt{\frac{r}{g}}\,\{\epsilon^{+l\sqrt{rg}} - \epsilon^{-l\sqrt{rg}}\} \end{aligned} \qquad (23)$$

(*d*) If the circuit, at $l = l_0$, is closed by a resistance r_0, we have

$$\left|\frac{e}{i}\right|_{l=l_0} = r_0$$

hence,

$$\frac{A_1\,\epsilon^{-l_0\sqrt{rg}} - A_2\,\epsilon^{+l_0\sqrt{rg}}}{A_1\,\epsilon^{-l_0\sqrt{rg}} + A_2\,\epsilon^{+l_0\sqrt{rg}}} = \frac{r_0}{\sqrt{\dfrac{r}{g}}}$$

$$\frac{A_2\, \epsilon^{+l_0 \sqrt{rg}}}{A_1\, \epsilon^{-l_0 \sqrt{rg}}} = \frac{\sqrt{\frac{r}{g}} - r_0}{\sqrt{\frac{r}{g}} + r_0}$$

or,

$$A_2 = A_1\, \epsilon^{-2 l_0 \sqrt{rg}}\, \frac{\sqrt{\frac{r}{g}} - r_0}{\sqrt{\frac{r}{g}} + r_0} \tag{24}$$

$$\begin{aligned} i &= A \left\{ \epsilon^{-l\sqrt{rg}} - \frac{r_0 - \sqrt{\frac{r}{g}}}{r_0 + \sqrt{\frac{r}{g}}}\, \epsilon^{-(2 l_0 - l)\sqrt{rg}} \right\} \\ e &= A \sqrt{\frac{r}{g}} \left\{ \epsilon^{-l\sqrt{rg}} + \frac{r_0 - \sqrt{\frac{r}{g}}}{r_0 + \sqrt{\frac{r}{g}}}\, \epsilon^{-(2 l_0 - l)\sqrt{rg}} \right\} \end{aligned} \tag{25}$$

These equations (**23**) and (**25**) can be written in various different forms. They are interesting in showing in a direct-current circuit, features which usually are considered as characteristic of alternating currents, that is, of wave motion.

The first term of (**23**) or (**25**) is the out-flowing or main current or voltage, respectively; the second term is the reflected one.

At the end of the circuit with distributed constants, reflection occurs at the resistance r_0.

If $r_0 > \sqrt{\frac{r}{g}}$, the coefficient of the second term is positive, and partial reflection of current occurs, while the return voltage adds itself to the incoming voltage.

If $r_0 < \sqrt{\frac{r}{g}}$, reflection of voltage occurs, while the return current adds itself to the incoming current.

If $r_0 = \sqrt{\frac{r}{g}}$, the second term vanishes, and the equations (**25**) become those of (**19**), of an infinitely long conductor. That is:

A resistance r_0, equal to the effective resistance (surge impedance) $\sqrt{\frac{r}{g}}$ of a direct-current circuit of distributed constants, passes current and voltage without reflection. A higher resistance r_0 partially reflects the voltage—completely so for $r_0 = \infty$, or open circuit. A lower resistance r_0 partially reflects the current—completely so for $r_0 = 0$, or short circuit.

$\sqrt{\frac{r}{g}}$ thus takes in direct-current circuits the same position as the surge impedance in alternating-current or transient circuits.

D. Alternating-Current Circuits with Distributed Constants

$$b = \pm j\,q$$

by equation (**7**), a then becomes a general number: $\pm\,(h \pm j\,k)$, and the corresponding values of b and a exist:

$$\begin{array}{ll} b = +j\,q, & a = +h - j\,k \\ \quad\;\; -j\,q & \quad\;\; +h + j\,k \\ \quad\;\; -j\,q & \quad\;\; -h - j\,k \\ \quad\;\; +j\,q & \quad\;\; -h + j\,k \end{array}$$

Substituting these in equation (**4**), and substituting for the exponentials with imaginary exponent the trigonometric expression, gives

$$i = \epsilon^{-hl}\,\{B_1 \cos\,(kl - qt) + B_2 \sin\,(k\,l - qt)\} \\ + \epsilon^{+hl}\,\{B_3 \cos\,(kl + qt) + B_4 \sin\,(k\,l + q\,t)\} \quad \textbf{(26)}$$

where

$$B_1 = A_1 + A_2 \qquad B_3 = A_3 + A_4$$
$$B_2 = j(A_1 - A_2) \qquad B_4 = j(A_3 - A_4)$$

Resolving now the trigonometric expression of (**26**) into expressions of single angles, and eliminating the function of time by the introduction of the vector notation,

$$B_1 \cos qt - B_2 \sin qt = B_1 - j\,B_2 = A_1.$$

$$B_2 \cos qt + B_1 \sin qt = B_2 + j\,B_1 = j\,A_1.$$

$$B_3 \cos qt + B_4 \sin qt = B_3 + j\,B_4 = -\,A_2.$$

$$B_4 \cos qt - B_3 \sin qt = B_4 - j\,B_3 = j\,A_2.$$

ol. 35
916

gives as the expression of the current,

$$I = A_1\,\epsilon^{-hl}(\cos kl + j\sin k\,l) - A_2\,\epsilon^{+hl}(\cos kl - j\sin kl) \qquad (27)$$

and in the same manner, starting with equation (5),

$$E = \sqrt{\frac{Z}{Y}}\,\{A_1\,\epsilon^{-hl}(\cos kl + j\sin kl) + A_2\,\epsilon^{+hl}(\cos kl - j\sin kl)\} \qquad (28)$$

where

$$Z = r + j\,q\,L$$
$$Y = g + j\,q\,C \qquad (29)$$
$$q = 2\,\pi\,f$$

These are the usual and well known equations of the alternating-current transmission line in symbolic expressions.

II. IMPULSE CURRENTS

A. General

Impulse currents are characterized by the condition, that the time exponent b in equations (4) and (5) is real.

By equation (7), to every value of b correspond two values of a, equal but of opposite sign:

$$\pm\, a$$

By the same equation, to every value of a correspond two values of b:

$$b = u \pm s \qquad (30)$$

where

$$s = \sqrt{m^2 + \frac{a^2}{L\,C}} \qquad (31)$$

is the *energy transfer constant,*

$$u = \frac{1}{2}\left\{\frac{r}{L} + \frac{g}{C}\right\} \qquad (32)$$

is the *energy dissipation constant,* and

$$m = \frac{1}{2}\left\{\frac{r}{L} - \frac{g}{C}\right\} \qquad (33)$$

is the *distortion constant* of the circuit.

As b must be positive, it must be, by (**30**)

$$s^2 \leqq u^2 \tag{34}$$

Since u and b are real, by (**30**), s must be real, thus by (**31**), $m^2 + \frac{a^2}{L\,C}$ must be real and positive.

As m^2 is real, $\frac{a^2}{L\,C}$ must be real, and must either be positive,

or, if negative, $-\frac{a^2}{L\,C}$ must be less than m^2.

a thus must be either real, or imaginary, but it can not be complex imaginary.

This gives two classes of impulse currents:

Non-periodic impulse currents: a real, a^2 positive.

Periodic impulse currents: a imaginary, a^2 negative, and $-a^2 \leqq L\,C\,m^2$

Vol. 35
1916

The terms "periodic" and "non-periodic" here refer to the distribution in space, but not in time, since as function of time the impulse currents are always non-periodic.

The relations between the constants thus are:

Non-periodic impulse currents:

$$\begin{aligned} a^2 &= \text{positive} \\ a &= \pm h \\ s &= \sqrt{m^2 + \frac{h^2}{L\,C}} \\ h &= \sqrt{L\,C\,(s^2 - m^2)} \\ u^2 \geqq\ & s^2 \geqq m^2 \end{aligned} \tag{35}$$

and corresponding values of a and b are:

$$\begin{array}{cc} a: & b: \\ +h & u-s \\ -h & u-s \\ -h & u+s \\ +h & u+s \end{array} \tag{36}$$

Periodic impulse currents:

$$\begin{aligned} a^2 &= \text{negative} \\ a &= \pm j\,k \\ s &= \sqrt{m^2 - \frac{k^2}{L\,C}} \\ k &= \sqrt{L\,C\,(m^2 - s^2)} \qquad (37) \\ s^2 &\leqq m^2 \\ k^2 &\leqq m^2\,L\,C \end{aligned}$$

and corresponding values of a and b are:

a:	b:
$+jk$	$u - s$
$-jk$	$u - s$
$+jk$	$u + s$
$-jk$	$u + s$

(38)

B. NON-PERIODIC IMPULSE CURRENTS

Substituting (**35**) and (**36**) in (**4**) and (**5**), and rearranging, gives:

$$i = \epsilon^{-ut}\left\{A_1\,\epsilon^{-hl+st} + A_2\,\epsilon^{+hl+st} + A_3\,\epsilon^{+hl-st} + A_4\,\epsilon^{-hl-st}\right\}$$

$$e = \sqrt{\frac{L}{C}}\,\epsilon^{-ut}\left\{c\,A_1\,\epsilon^{-hl+st} - c\,A_2\,\epsilon^{+hl+st} + \frac{1}{c}\,A_3\,\epsilon^{+hl-st} - \frac{1}{c}\,A_4\,\epsilon^{-hl-st}\right\} \qquad (39)$$

where

$$c = \sqrt{\frac{s+m}{s-m}} \qquad (40)$$

These equations (**39**) can be simplified by shifting the zero points of time and distance, by the substitution:

$$\begin{aligned} A_1 &= D_1\,\epsilon^{+hl_1 - st_1} \\ A_2 &= D_2\,\epsilon^{-hl_1 - st_1} \\ A_3 &= \pm\,D_1\,\epsilon^{-hl_1 + st_1} \qquad (41) \\ A_4 &= \pm\,D_2\,\epsilon^{+hl_1 + st_1} \end{aligned}$$

$$c = \epsilon^{+st_0} \qquad (42)$$

Hence

$$t_0 = \frac{\log c}{s} = \frac{1}{2s} \log \frac{s+m}{s-m} \tag{43}$$

and writing t for $t - t_1 + t_0$

and l for $l - l_1$

they then assume the form:

$$i = \epsilon^{-ut} \{D_1 [\epsilon^{-hl+s(t-t_0)} \pm \epsilon^{+hl-s(t-t_0)}] - D_2 [\epsilon^{+hl+s(t-t_0)} \pm \epsilon^{-hl-s(t-t_0)}]\} \tag{44}$$

$$e = \sqrt{\frac{L}{C}}\, \epsilon^{-ut} \{D_1 [\epsilon^{-hl+st} \pm \epsilon^{+hl-st}] + D_2 [\epsilon^{+hl+st} \pm \epsilon^{-hl-st}]\}$$

or, expressed in hyperbolic functions:

$$i = \epsilon^{-ut} \{B_1 \cosh [hl - st(t - t_0)] - B_2 \cosh [hl + s(t - t_0)]\} \tag{45}$$

$$e = \sqrt{\frac{L}{C}}\, \epsilon^{-ut} \{B_1 \cosh [hl - st] + B_2 \cosh (hl + st]\}$$

or the corresponding sinh functions, in case of the minus sign in equation (**44**).

The impulse thus is the combination of two single impulses of the form

$$\epsilon^{-ut} (\epsilon^{-hl+st} \pm \epsilon^{+hl-st})$$

which move in opposite direction, the D_1 impulse towards rising l: $\frac{dl}{dt} > 0$, and the D_2 impulse towards decreasing l: $\frac{dl}{dt} < 0$.

The voltage impulse differs from the current impulse by the factor $\sqrt{\frac{L}{C}}$ (the "surge impedance"), and by a *time displacement* t_0. That is, in the general impulse, voltage e and the current i are displaced in time.

t_0 thus may be called the time displacement, or time lag of the current impulse behind the voltage impulse.

t_0 is positive, that is, the current *lags* behind the voltage impulse, if in equation (**43**) the log is positive, that is, m is positive,

or: $\frac{r}{L} > \frac{g}{C}$, that is, the resistance-inductance term preponderates.

Inversely, t_0 is negative, and the current *leads*, or the voltage impulse lags behind the current impulse, if m is negative, that is, $\frac{r}{L} < \frac{g}{C}$, or the capacity term preponderates.

If $g = 0$, that is, no shunted conductances, the current impulse always lags behind the voltage impulse.

If $m = 0$, that is, $\frac{r}{L} = \frac{g}{C}$, or $\frac{r}{g} = \frac{L}{C}$, $t_0 = 0$, that is, the voltage impulse and the current impulse are in phase with each other, that is, there is no time displacement, and current and voltage impulses have at any time or at any space the same shape; *distortionless circuit.* m therefore is called the *distortion constant* of the circuit.

In the individual impulse

$$\epsilon^{-u}\left(\epsilon^{-hl+st} \pm \epsilon^{+hl-st}\right) = \epsilon^{-hl}\,\epsilon^{-(u-s)t} \pm \epsilon^{+hl}\epsilon^{-(u+s)t} \qquad \textbf{(46)}$$

the term ϵ^{-ut} is the attenuation of the impulse by the energy dissipation in the circuit, that is, represents the rate at which the impulse would die out by its energy dissipation.

The first term: $\epsilon^{-(u-s)t}$, dies out at a slower rate than given by the energy dissipation, that is, in this term, at any point l, energy supplied is left behind by the passing impulse, and as the result, this term decreases with increasing distance l, by the factor ϵ^{-hl}; inversely, the second term, $\epsilon^{-(u+s)t}$, dies out more rapidly with the time, than corresponds to the energy losses, that is, at any point l, this term abstracts energy and shifts it along the circuit, and thereby gives an increase of energy in the direction of propagation, by ϵ^{+hl}. In other words, of the two terms of the impulse, the one drops energy while moving along the line, and the other picks it up and carries it along.

The terms $\epsilon^{\pm st}$ thus represent the dropping and picking up of energy with the time, the terms $\epsilon^{\pm hl}$ the dropping and picking up of energy in space along the line. In distinction to u, which may be called the *energy dissipation constant*, s (and its corresponding h) thus may be called the *energy transfer constant* of the impulse. The higher s is, the greater then is the rate of energy transfer, that is, the steeper the wave front, and s thus may also be called the *wave front constant* of the impulse.

Substituting in equations (**44**), $l = 0$, gives the equation of the impulse in a circuit with massed constants:

$$i = A\,\epsilon^{-ut}\left(\epsilon^{+st} \pm \epsilon^{-st}\right)$$

$$e = B\sqrt{\frac{L}{C}}\,\epsilon^{-ut}\left(\epsilon^{+s(t-t_0)} \pm \epsilon^{-s(t-t_0)}\right)$$

where

$$A = D_1 - D_2$$
$$B = D_1 + D_2.$$

Substituting in equation (**39**),

$$\begin{aligned} A_1 &= \pm B\,\epsilon^{+hl_1 - st_1 + x} \\ A_2 &= \pm B\,\epsilon^{-hl_1 - st_1 - x} \\ A_3 &= \pm B\,\epsilon^{-hl_1 + st_1 + x} \\ A_4 &= \pm B\,\epsilon^{+hl_1 + st_1 - x} \end{aligned} \qquad (\mathbf{47})$$

$$c = \epsilon^{+st_0} \qquad (\mathbf{42})$$

and writing

$$t \text{ for } t - t_1 + t_0 + \frac{x}{s}$$

$$l \text{ for } l - l_1$$

and rearranging, gives

$$\begin{aligned} i &= B\,\epsilon^{-ut}\left\{\epsilon^{-hl}\left[\epsilon^{+s(t-t_0)} \pm \epsilon^{-s(t-t_0)}\right] \pm \epsilon^{+hl}\left[\epsilon^{+s(t-t_0-t')} \pm \epsilon^{-s(t-t_0-t')}\right]\right\} \\ e &= B\sqrt{\frac{L}{C}}\,\epsilon^{-ut}\left\{\epsilon^{-hl}\left[\epsilon^{+st} \pm \epsilon^{-st}\right] \pm \epsilon^{+hl}\left[\epsilon^{+s(t-t')} \pm \epsilon^{-s(t-t')}\right]\right\} \end{aligned} \qquad (\mathbf{48})$$

where

$$t' = \frac{2x}{s} \qquad (\mathbf{49})$$

writing

$$t \text{ for } t - t_1 + t'$$

$$l \text{ for } l - l_1 + \frac{x}{h}$$

the substitution of (**47**) and (**42**), gives, after rearranging,

$$i = B\,\epsilon^{-ut}\left\{\epsilon^{-s(t-t_0)}\left[\epsilon^{+hl} \pm \epsilon^{-hl}\right] \pm \epsilon^{+s(t-t_0)}\left[\epsilon^{+h(l-l')} \pm \epsilon^{-h(l-l')}\right]\right\}$$

$$e = B\sqrt{\frac{L}{C}}\,\epsilon^{-ut}\left\{\epsilon^{-st}\left[\epsilon^{+hl} \pm \epsilon^{-hl}\right] \pm \epsilon^{+st}\left[\epsilon^{+h(l-l')} \pm \epsilon^{-h(l-l'}\right]\right\} \qquad \textbf{(50)}$$

where

$$l' = \frac{2\,x}{h} \qquad \textbf{(51)}$$

Equations (**48**) may be interpreted as showing two impulses, the main impulse, and the reflected impulse. The main impulse, with ϵ^{-hl}, decreases with increasing l, that is, progresses towards rising l. The reflected impulse, with ϵ^{+hl}, starts at the time t' after the start of the main impulse, and decreases with decreasing l, that is, progresses towards decreasing l.

The two current impulses lag behind their voltage impulse by time t_0.

Equation (**50**) shows the two component impulses, the first one dropping energy along its path, and thus decreasing with the time at a greater rate than corresponds to the energy dissipation, and the second one, displaced in position from the first one by distance l^1, picking up the energy dropped by the first one.

The current again lags behind the voltage by time t_0.

The distance displacement l^1 of the component impulse in (**50**) is related to the time displacement t' of the two component impulses in (**48**) by (**49**) and (**51**):

$$\frac{l'}{t'} = \frac{s}{h}$$

that is, l' is the distance traveled by the impulse during time t'.

In hyperbolic functions, equations (**50**) may be written:

$$i = B\,\epsilon^{-ut}\,\{\epsilon^{-s\,(t-t_0)}\cosh hl \pm \epsilon^{+s\,(t-t_0)}\cosh h\,(l-l')\}$$

$$e = B\sqrt{\frac{L}{C}}\,\epsilon^{-ut}\,\{\epsilon^{-st}\sinh h\,l \pm \epsilon^{+st}\sinh h\,(l-l')\} \qquad (52)$$

C. Periodic Impulse Currents

Substituting (**37**) and (**38**) in (**4**) and (**5**), separating the imaginary exponentials from the real ones, substituting the trigonometric expressions for the former, and rearranging, gives

$$i = \epsilon^{-ut}\,\{\epsilon^{-st}\,[D_1\cos kl - D_2\sin kl] + \epsilon^{-st}\,[D_3\cos kl - D_4\sin kl]\}$$

$$e = \sqrt{\frac{L}{C}}\,\epsilon^{-ut}\,\{c\,\epsilon^{+st}\,[D_2\cos kl + D_1\sin kl] + \frac{1}{c}\,\epsilon^{-st}\,[D_4\cos kl + D_3\sin kl]\} \qquad (53)$$

where

$$c = \sqrt{\frac{m+s}{m-s}} \qquad (54)$$

Substituting:

$$\begin{aligned} D_1 &= \pm B\,\epsilon^{-st_1}\cos kl_1 \\ D_2 &= \pm B\,\epsilon^{-st_1}\sin kl_1 \\ D_3 &= \pm B\,\epsilon^{+st_1}\cos k\,(l_1-l_0) \\ D_4 &= \pm B\,\epsilon^{+st_1}\sin k\,(l_1-l_0) \end{aligned} \qquad (55)$$

$$c = \epsilon^{+st_0} \qquad (56)$$

Thus,

$$t_0 = \frac{\log c}{s} = \frac{1}{2\,s}\,\log\frac{m+s}{m-s} \qquad (57)$$

and writing

t for $t - t_1 + t_0$
l for $l + l_0$

gives

$$i = B\,\epsilon^{-ut}\,\{\epsilon^{+s\,(t-t_0)}\cos kl \pm \epsilon^{-s\,(t-t_0)}\cos k\,(l-l_0)\}$$

$$e = B\sqrt{\frac{L}{C}}\,\epsilon^{-ut}\,\{\epsilon^{+st}\sin kl \pm \epsilon^{-st}\sin k\,(l-l_0)\} \qquad (58)$$

Exchanging sin and cos in (**55**), also exchanges sin and cos in (**58**).

Equations (**58**) of the periodic impulse have the same form as equations (**52**) of the non-periodic impulse, except that the trigonometric functions of distance take in the periodic impulse the same position as the hyperbolic function in the non-periodic impulse.

Current and voltage are in quadrature with each other in their distribution in space, in either of the two components of the periodic impulse. That is, in each of the two components maximum current coincides with zero voltage, and inversely.

The two components of the periodic impulse differ in the phase of their space distribution by the distance l_0, the second component lagging behind the first component by the distance l_0.

In each of the two components of the periodic impulse, the current lags behind the voltage by the time t_0.

Current and voltage thus are in quadrature with each other in space, and displaced from each other in time, by the " *time* displacement " t_0.

t_0 is positive, that is, the current lags behind the voltage by time t_0, if m is positive, and t_0 is negative, that is, the current leads the voltage, if m is negative.

Since $m = 1/2\left(\frac{r}{L} - \frac{g}{C}\right)$ it follows:

The current lags behind the voltage, if $\frac{r}{L} > \frac{g}{C}$, that is, if the resistance-inductance effect preponderates.

The current leads the voltage if $\frac{g}{C} > \frac{r}{L}$, that is, if the capacity effect preponderates.

The voltage equals the current times the surge impedance $z = \sqrt{\frac{L}{C}}$, but is in quadrature with it in space, and the current is lagging by t_0 in time.

By the conditions of existence of the periodic impulse, s must numerically be smaller than m.

$$s = 0 \text{ gives}$$

$$\text{by } (\mathbf{57}): \quad s t_0 = 0.$$

$$\text{by } (\mathbf{37}): \quad k = m \sqrt{L C}$$

and by (58),

$$i = B\,\epsilon^{-ut}\,\{\cos k\,l' \pm \cos k\,(l' - l_0)\}$$

$$e = B\sqrt{\frac{L}{C}}\,\epsilon^{-ut'}\,\{\sin k\,l' \pm \sin k\,(l' - l_0)\}$$

Hence, current and voltage are in phase in time, but in quadrature in space.

$s = m$ gives

$$k = 0$$

hence, from (53),

$$i = \epsilon^{-ut}\,(D_1\,\epsilon^{+mt} + D_3\,\epsilon^{-mt})$$

$$e = \sqrt{\frac{L}{C}}\,\epsilon^{-ut}\,(D_2\,\epsilon^{+m\,(t+t_0)} + D_4\,\epsilon^{-m\,(t+t_0)})$$

hence, substituting for u and m,

$$i = D_1\,\epsilon^{-\frac{g}{C}t} + D_3\,\epsilon^{-\frac{r}{L}t}$$

$$e = \sqrt{\frac{L}{C}}\,\left\{D_2'\,\epsilon^{-\frac{g}{C}(t+t_0)} + D_4'\,\epsilon^{-\frac{r}{L}(t+t_0)}\right\}$$

where

$$D_2' = D_2\,\epsilon^{+ut_0}$$

$$D_4' = D_4\,\epsilon^{+ut_0}$$

In this impulse, the capacity terms and the inductance terms are separate, and current and voltage are uniform throughout the entire circuit.

The constants D or A or B are determined, as integration constants, by the terminal conditions of the problem.

For instance, if at the starting moment of the impulse, that is, at time $t = 0$, the distribution of current and of voltage throughout the circuit are given, we have by (**53**), for $t = 0$,

$$i = \{D_1 + D_3) \cos kl - (D_2 + D_4) \sin kl\}$$

$$e = \sqrt{\frac{L}{C}} \left\{ \left(c\, D_2 + \frac{D_4}{c}\right) \cos kl \right.$$

$$\left. + \left(c\, D_1 + \frac{D_3}{c}\right) \sin kl \right\}$$

The development of the given distribution of current and voltage into a Fourier series thus gives in the coefficients of this series the equations determining the constants D_1, D_2, D_3, D_4.

The expressions for i and e, given in equations (**39**), (**44**), (**45**), (**48**), (**50**) and (**52**) for the non-periodic, and in equations (**53**) and (**58**) for the periodic impulse, obviously apply to a simple impulse only, and a general impulse is represented by the sums $\Sigma\, i$ and $\Sigma\, e$ of all the expressions i and e, whose integration constants satisfy the terminal conditions of the problem.

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Discussion on "Outline of Theory of Impulse Currents" (Steinmetz), New York, Jan. 14, 1916.

Charles P. Steinmetz: "Outline of Theory of Impulse Currents" is a continuation of the paper on the general equation of the electric circuit, read eight years ago. In the previous paper it was found that the general differential equation, which applies to every electric circuit or section of circuit having constant values of r, L, g, and C, can be integrated by an expression consisting of four terms, two main waves and their two return waves. One of the waves dies out at a greater, the other at a slower rate than corresponds to the energy dissipation in the circuit, and therefore the former transfers energy to the latter, thus representing the energy transfer along the circuit, as occurring in traveling waves, a-c. transmission etc. These two waves coincide, and the energy transfer coefficient becomes zero, in the stationary oscillation of a uniform circuit; they do not coincide, however, in the stationary oscillation of a compound circuit, but energy transfer occurs from sections of lower energy dissipation, to sections of higher energy dissipation.

In the first part of the present paper, a classification of the different types of electric current is made from the general equation of the electric circuit, and in the second part, various forms of the equations of the general impulse currents are derived.

Two methods of studying engineering phenomena exist, which may be denoted respectively as the *synthetic* method and the *analytic* method.

The synthetic method starts with the study of special cases, and by correlation of the special cases, by generalization and classification progresses from special to general, and thus finally to the complete structure of the engineering science.

The analytic method starts from the general (differential) equation of the science based on the fundamental underlying laws, and by substituting all the possible values of the constants and the terminal conditions, thereby derives the different classes of the phenomena, thus progressing from the most general to the special.

As engineering is based on experience, and experiment necessarily deals with special cases, the synthetic method is the first in the development of engineering, and the analytic method, requiring the knowledge of the fundamental laws, can be attempted only later.

However, the synthetic method can never give assurance of the completeness of our knowledge, for entire classes of phenomena may be omitted, if it happens that they have never been empirically observed or recognized. Inversely, the analytic method gives the complete structure, but only so far as it is based on the fundamental laws represented by the general equation, and thus may not be comprehensive, since any phenomenon which does not obey these laws, would not be included.

Thus the two methods are supplementary, the analytic method checking the completeness of the synthetic, and the synthetic checking the comprehensiveness of the analytic.

The theory of electrical engineering, relating to direct currents, alternating currents, exponential discharges, oscillating currents and other transients, was developed synthetically; and the purpose of the first part of the present paper is, by the analytic method, to derive all possible types of currents by substituting all possible values of constants and of terminal conditions, and thereby check, whether any class of current of industrial importance has escaped recognition. This appears probable, as the observed transmission line phenomena do not entirely agree with the characteristics of the currents by which they are usually explained.

During the development of high-voltage long-distance transmission, phenomena were observed during disturbances in the transmission lines or underground cables, which could not be explained by the normal voltage supplied by the generating machinery. The first attempt at explanation was made in the study of the "natural period" of the circuit, the abnormal voltages resulting from the free oscillation of the line as a quarter wave (or half wave or full wave), and its higher harmonics. In a few instances this agreed fairly well with the facts, thus pointing to quarter-wave oscillations as possible line disturbances. Usually, however, it did not agree for a quarter wave oscillation would be felt over the entire circuit, whereas experience showed most line disturbances were more local in character, that is, very severe at some places, but rapidly decreasing with the distance. It further showed, as characteristic, the piling up of voltage locally, especially at inductive parts of the circuit, such as transformer end turns, inductances, current transformers etc. This led to the explanation of the disturbance as due to high frequency. High-frequency travelling waves would give local abnormal voltage, and rapid attenuation with the distance from the origin, and therefore would satisfactorily explain the most frequent line disturbances, except in one feature, namely, that such high-frequency oscillating currents should give pronounced resonance effects. Such resonance effects, leading to the formation of stationary oscillations of destructive value, have been observed and experimentally reproduced in recent years, in the high-potential windings of high-voltage power transformers, usually of frequencies between 10,000 and 100,000 cycles, and their existence has therefore been proved. However, in most cases of transmission line disturbances, resonance phenomena are remarkably weak or entirely absent, and it therefore appears that many transmission line disturbances are impulsive rather than oscillatory, which has led to the question of the existence, the characteristics and the equations of impulse currents.

In a circuit with localized capacity, inductance and resistance, the current is either oscillatory or impulsive, depending on the circuit constants, and more particularly the relation of the resistance to the inductance and capacity. In a circuit with distributed constants, however, there is no critical value of constants, that divides the oscillatory and the impulsive phenomena, but, as was shown in the paper of 1908, with the same circuit constants, the phenomena may be oscillatory or they may be impulsive, depending on the terminal conditions, that is, on the cause of the phenomena. Thus oscillating currents as well as impulse currents may exist in the same circuit, although experience seems to show, that at least in long distance transmission lines the latter are rather the more frequent.

To get their relation to the other and better known classes of current, was the purpose of the first part of the present paper.

1. Terminal conditions. The foremost terminal condition is the length l of the circuit. This may be either zero, or finite, or infinite. Substituting $l = 0$ gives the equation of circuits with massed constants: the usual a-c. or d-c. circuits of our systems and apparatus, etc. l = finite gives the equation of circuits with distributed constants and $l = \infty$ gives the case where the circuit is so long, that the disturbance has decreased to a negligible value before reaching the end of the circuit, and thus the reflected disturbance is inappreciable.

2. Constants. The general integral equation of the electric circuit appears as an exponential function, with the time and the distance in the exponent. It thus has a coefficient of the time exponent, b, and a coefficient of the distance exponent, a. a and b are related by a quadratic equation, thus only one is independent, b has been chosen as the independent coefficient. b is a general (or complex imaginary) number, and the two main special cases thus are, (a) where the real term of b is zero, (b) where the imaginary term is zero. (a) gives the alternating currents. (b) gives a non-periodic class of transient currents, which may be called the *impulse currents*. The impulse currents thus appear as a class of currents, as general as, and coordinate with the alternating currents, the latter representing the useful currents of our transmission systems, the impulse currents the foremost type of harmful currents.

The second part of the present paper contains a further classification of the impulse currents, by their distribution along the circuit, as non-periodic and periodic in space, and a derivation of various forms of the equations of the two classes of impulse currents.

Physically, impulse currents, by the steepness of their wave front, give the local piling up of voltage, characteristic of most line disturbances, but as non-periodic currents, they could give resonance phenomena only by multiple reflection, and thus resonance phenomena with impulse currents would be little pronounced or absent.

It appears, therefore, that the most frequent disturbances of our transmission systems show the characteristics of the impulse currents rather than those of oscillating currents, and the study of impulse currents becomes of far greater importance than heretofore assumed.

Thus, the analytic study led to the recognition of the impulse currents as a class of currents, which, while not unknown before, but repeatedly mentioned and discussed, apparently has not sufficiently been realized in respect to its industrial importance.

The reverse operation would now be of interest: to check by the synthetic method, the completeness of the analytic structure, that is, to see to what extent existing or at least industrially important classes of currents are not contained within the scope of the general equation based on constancy of r, L, g and C.

Phenomena are known, which are outside of this equation. Such phenomena are the cumulative oscillations, such as are produced under certain conditions by an arc (not the phenomena of the so-called 'arcing ground;' these are recurrent oscillating discharges), the surging of synchronous machines, the phenomena in circuits operating above corona voltage, etc.

Thus the general equation of the electric circuit, which is the starting point of the present paper and the previous paper, is not all comprehensive, but a still more general analytical investigation is desirable, in which r, L, g and C are not constant, but depend on $\frac{di}{dt}$ and $\frac{de}{dt}$ or an integrated value thereof, as the frequency, etc. Our knowledge of these phenomena is not yet sufficient to attempt an analytic treatment, but more knowledge will have to be acquired by the synthetic method of investigating special classes of phenomena, in a way similar to that attempted with the surging of synchronous machines in the paper on "Instability of Electric Circuits" read before the Chicago Section in 1912.

M. I. Pupin: If I understand Dr. Steinmetz, the object of his paper is to call your attention to a distinct class of electric currents, a class of electric currents which he calls impulse currents and which, he says, has not received as much attention as the direct current and the alternating current. When I saw the notice of the paper and observed the title "Outline of Theory of Impulse Currents," it attracted me very much, because I have always been interested in impulse currents. To me the direct current and the alternating current were simply cases of the more general impulse current.

When Dr. Steinmetz says that equations (**4**) and (**5**) "must represent every existing electric circuit, and every circuit which can be imagined, from the lightning discharge to the house bell, and from the a-c. transmission line to the telephone circuit, with the only limitation, that r, g, L, C are constant within the range of the currents and voltage considered," he should not be misunderstood in his statement, and I believe that he might be misunderstood. I wish to warn you not to misunderstand that statement, because if you do, you might think that after you read this article you need not read anything else on this subject, so, therefore, I want to warn you against that.

Here Dr. Steinmetz considers the general problem on a long line having distributed inductance, resistance and capacity, and he gives you that, starting from a differential equation. What do we mean by differential equations in electricity? We mean simply this—an equation expressing the various relations between the reactions in a conductor. For instance, take the first equation Dr. Steinmetz gives, which looks so mathematical—as a matter of fact it is nothing more nor less than the expression that in any element of conductor the sum of the electrical actions is equal to the sum of the electrical reactions. That is what he says, and that is Newton's third law of motion, that the sum of action is equal to the sum of reactions in every system of bodies.

Dr. Steinmetz says—Suppose there is that relation between these various electrical reactions and various electrical actions, then the following must be the relation between the current and e.m.f. in any part of the circuit. That is what is called the integral of it. From the equation of reactions you get an expression of the current and the e.m.f., and that is called the integral. That is true for any point of the wire which has certain constants.

Now, when you come to another point of the wire where other constants are, then you have to get another expression for the currents, and since you have an infinite number of points, you may have an infinite number of different expressions for the current, and it is necessary to add these different currents and make them conform to the so-called boundary conditions. As soon as you pass from one element of the wire with certain constants, to another element of the wire with another set of constants, you have to pass through that boundary.

The most difficult thing in mathematical analyses of electrical phenomena is that question of the boundary conditions. So that when Dr. Steinmetz says "These equations must represent every existing electric circuit," he does not mean to say that he has given you a complete solution—he means to say that he has given you a complete solution for any part of the electric circuit, but if you want to have a complete solution, good for any part and for the complete circuit, you have to take this part, and this part, and this part and build it up. That explains the point I had in mind.

It is true that there are problems in electrical engineering which have not been discussed at all, and Dr. Steinmetz has referred to one of those problems which has interested me for years, the problem of the oscillating arc. It may be that in some oscillating arcs the oscillation is due to the variable resistance. It may be. But the electrical oscillation that takes place in a vacuum tube, such as the pliotron tube, is not due to variable resistance, but is due to something else. That is to say, the oscillating arc acts in a very similar manner to the oscillations produced by an induction motor when you drive it beyond synchronism. Take a single-phase induction motor, drive it beyond synchronism, and provide it with a suitable capacity, and you can get oscillations exactly the same as you do in an oscillating wire in the pliotron tube—there is no variable resistance, there is no variable capacity, there is no variable inductance, the only thing that is variable is the mutual inductance between the primary and secondary circuit.

Dr. Steinmetz to my knowledge has not attempted yet to proceed analytically and pursue this elusive induction motor to see what it will do under certain conditions, but undoubtedly he will, and when he does he will find that an induction motor, whether it is single-phase or polyphase, when supplied with proper capacity and constructed suitably can generate these oscillations in just the same way as the pliotron tube or the oscillating arc. Moreover, if he does not take the proper precaution, the oscillations stored in an induction motor of that kind will be oscillations, not with a negative exponent, but with a positive exponent; that is to say, the oscillations will go on increasing indefinitely until his machine is smashed. The machine has to obey the integral of that differential equation, that is to say, the machine has to obey the law of the electrical reactions. The mechanical power that drives the motor acts, the motor reacts, and the result of that action and reaction is continually piling up energy which appears as magnetic energy, and when the current is big enough, of course, your machine will be either smashed, or the pole pieces will be crushed on to the armature and the machine will come to a standstill.

Harold Pender: Dr. Steinmetz has given us an interesting mathematical discussion of an important class of electric phenomena. It is not difficult to see the physical meaning of the mathematical symbols used in the differential equations given in the paper, but this is not true of many of the symbols appearing in the integral equations. For example, on the last page of the paper there are certain constants enumerated, namely, D_1, D_2, D_3, D_4. What are they? In mathematical language they are called integration constants, and physically they have a definite relation to the physical conditions intially imposed on the circuit, *i.e.*, they depend upon the voltage and current initially established at each point of the circuit. But how may these constants be evaluated in terms of these initial conditions? I hope that Dr. Steinmetz will give us at some future time a discussion not only of the *qualitative* meaning of these constants, which is not difficult to see, but also their *quantitative* values for various initial conditions which may occur in practise.

The differential equation (**3**) in this paper is one that contains, as Dr. Steinmetz has said, a complete solution of single-circuit lines. By a single-circuit line I mean a circuit which does not contain mutual inductance. If there is mutual inductance a second equation is necessary, and the evaluation of the exponents in the various integral relations requires the solution of a cubic equation instead of a quadratic. When there is mutual inductance between the given circuit and more than one other circuit, the evaluation of the exponents requires the solution of an equation of still higher degree. I give this merely to emphasize the fact that the relations given in the paper apply only to a single circuit which is not influenced by any neighboring circuit, a condition which seldom obtains in any transmission system.

Hans Lippelt: The paper, after introducing equations (**1**) and (**2**), puts forward the following statement:

"These equations must represent every existing electric circuit, and every circuit which can be imagined, from the lightning discharge to the house bell, and from the a-c. transmission line to the telephone circuit, with the only limitation, that *r*, *g*, *L*, *C* are constant within the range of the currents and voltages considered."

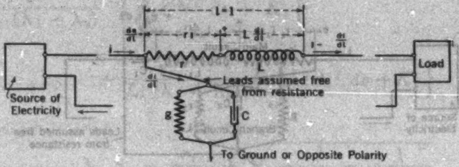

FIG. 1

By a peculiar coincidence, it occurred to me that these equations might not include all cases which are situated between the limits given in that statement. As a matter of fact, Dr. Steinmetz in concluding the presentation of the paper tonight mentioned several cases which are not included in these equations. He limited himself, however, again by saying that the cited cases involve variations of the "constants."

To me it seems that there is still another possibility of an electric circuit, which is not covered by equations (**1**) and (**2**). The circuit I have in mind contains capacity in series connection.

Fig. 1 shows in a general way an elementary circuit to which Dr. Steinmetz's equations (**1**) and (**2**) have reference. The figure will be readily understood by observing the notations used in the paper. The whole circuit is composed of a series of such elementary circuits.

If we have a capacity C_1 in series with the circuit, the latter may be represented as shown in Fig. 2. It is not feasible, however, to assume capacity in each elementary circuit, because the capacity of the total circuit would then be so small that no current at all could flow. The new fundamental equation should, therefore, not refer to the change of voltage per unit length of line $\left(\frac{de}{dl}\right)$, but to a voltage drop in a circuit with massed constants. The length of circuit as such does then not enter into the computation.

If e, the consumed voltage, and the other quantities r_1, r_2, L_1, L_2, C_1, C_2, g, refer to the circuit as per Fig. 2, we have

$$e = r_1 i_1 + L_1 \frac{di_1}{dt} + \frac{1}{C_1} \int i_1 \, dt \tag{1}$$

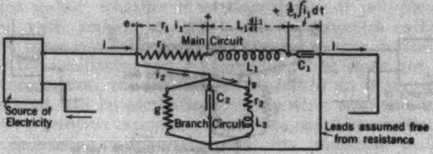
e
$r_1 i_1$
$+$
$L_1 \frac{di_1}{dt}$
$+ \frac{1}{C_1}\int i_1 dt$
i
r_1
Main Circuit
L_1
C_1
i
i_2
i_s
g
C_2
r_2
L_2
Branch Circuit
Source of Electricity
Leads assumed free from resistance

FIG. 2

Similarly, the current diverted from main circuit is, allowing also for self-induction L_2 combined with resistance r_2,

$$i_2 = ge + C_2 \frac{de}{dt} + i_k \times \epsilon^{-\frac{r_2}{L_2}t} + \frac{\epsilon^{-\frac{r_2}{L_2}t}}{r_2} \int e \, d\, \epsilon^{+\frac{r_2}{L_2}t} \tag{2}$$

wherein i_k is defined by the following:

$$\text{for } t = 0 \qquad \begin{cases} i_s = i_0 \\ e = e_0 \end{cases}$$

$$i_k = i_0 - \frac{e_0}{r_2} + \frac{1}{r_2} \int_{\substack{t=0 \\ \text{const.}=0}} \epsilon^{+\frac{r_2}{L_2}t} \, de$$

finally

$$i = i_1 + i_2 \tag{3}$$

To solve equations (**1**) and (**2**) requires the knowledge of e as a function of the time, and in this respect these equations differ materially from equations (**1**) and (**2**) of the paper. The latter refer to gradients of quantities $\left(\frac{de}{dl} \text{ and } \frac{di}{dl}\right)$, which are independent of actual values of e and i. Equations (**1**) and (**2**) refer to the quantities e and i directly, of which e is equal to the impressed voltage, which governs the whole process, viz., the vector sum of all secondary e.m.fs. must equal e. In the case of Fig. 1, forming only a small part of a large circuit, this partial circuit may draw stored power from adjacent circuits, involving an adjustment of its terminal voltage, and therefore equations (**1**) and (**2**) of the paper must leave this possibility open, which they do.

A partial, or rather advanced solution of equation (**1**) is given in equation (**4**).

$$i_1 = \frac{\epsilon^{\lambda_1 t}}{L_1\,(\lambda_1 - \lambda_2)} \left\{ \int \epsilon^{-\lambda_1 t}\, de + K_1 \right\}$$

$$- \frac{\epsilon^{\lambda_2 t}}{L_1\,(\lambda_1 - \lambda_2)} \left\{ \int \epsilon^{-\lambda_2 t}\, de + K_2 \right\} \qquad (\mathbf{4})$$

with
$$\lambda_1 = -\frac{r_1}{2L_1} + \sqrt{\frac{r_1^2}{4L_1^2} - \frac{1}{C_1 L_1}}$$

$$\lambda_2 = -\frac{r_1}{2L_1} - \sqrt{\frac{r_1^2}{4\,L_1^2} - \frac{1}{C_1\,L_1}}$$

K_1 and K_2 = integrating constants.

The last two terms on the right-hand side of equation (**2**) represent the current flowing through the branch loaded with inductance L_2 and resistance r_2, Fig. 2. These terms have been found by treating this branch separately.

To complete the solution of equation (**2**) requires only the substitution of the supposedly known value of e (as a function of time) and carrying out a simple mathematical process.

An application of a circuit with capacity is found in high-voltage d-c. machines, having armature windings of the open coil type. Such machines work entirely with impulse currents and it appears that circuits as per Fig. 2, or similar, will meet the requirements for sparkless commutation of current in the windings.

A. E. Kennelly (by letter): The great advantages of the analytical method set forth in Dr. Steinmetz's valuable paper are:

(1) The integral or primitive equations for all voltage and current waves over conductors are reduced to their simplest fundamental elements.

(2) These equations (**4**) and (**5**) of the paper permit of a new classification of all such voltage and current waves.

When b contains a real component, the paper shows that the wave to which it pertains must speedily disappear. Only when b has no real component can the wave to which it pertains belong to a permanent regime.

There are three cases involving real components of b; namely,

b complex, representing oscillatory transients (1)

b real $\begin{cases} \text{with } a \text{ real, representing non-oscillatory transients} & (2) \\ \text{with } a \text{ imaginary, representing non-oscillatory transients.} & (3) \end{cases}$

The paper distinguishes the two last types by the terms "non-periodic" and "periodic" impulses respectively. But these terms seem to be unsuitable because they suggest recurrence in time; whereas the property in question is a recurrence in distance or space. Would it not therefore be more appropriate to coin the terms "*non-spacic*" and "*spacic*" for this differentiation?

In any case, although the oscillatory and non-oscillatory transients should clearly be distinguished and placed in separate categories, it seems doubtful whether there is enough distinction between the two classes (2) and (3) of the non-oscillatory transients to make their separation important. The paper shows that the only essential difference between these two types is that where a circular distance-angle occurs with the one, a hyperbolic distance-angle occurs correspondingly with the other. Thus both are included in the same generalized trigonometric relations and it remains to be shown whether the differences between them are otherwise great enough to call for separate discussion.

It is perhaps going too far to say that all impulses with real b exponential time-factors are harmful; although the generalization may at present be applied to light and power circuits. In some signaling circuits, as in some submarine cable circuits, such impulses discharging back to ground at the sending end are usefully employed in certain signaling systems.

Charles P. Steinmetz: In regard to the general equation, which I gave in my paper eight years ago, naturally I did not mean that this equation is a final solution of every phenomenon; if I did, I would not have had any reason to write this paper. What I mean to say is that from this equation can be derived the equations of any circuit which fulfills the condition that every one of these four constants r, g, L and C is constant. Where one is variable, whether resistance, or inductance, or the capacity or conductance, then this general equation does not apply. I mentioned, as an illustration, a couple of circuits where the constants are variable. The transmission line, when operated above corona voltage, also gives a periodically variable conductance.

I referred to the oscillating arc. There I referred to the variable resistance. In the arc it is really a variable effective resistance, as I may call it, defining, as I have done here, resistance as the coefficient of energy dissipation proportionate to the current. The induction machine driven above synchronism also produces oscillations. These oscillations produced by the induction machine when driven above synchronism were discussed in my paper on "Induction Motors" 19 years ago, and their characteriscurves calculated. In the chapter on the "Induction Generator" in "Alternating Current Phenomena," a full discussion is found on the conditions under which an induction machine above synchronism excites, of the maximum voltage and current values to which it may build up, and its dependency on the constants of the external circuit. It may be interesting to note that two such induction generators of 10,000 kw. each, have been in operation for years in the Interborough Rapid Transit station in New York City, as generators producing power.

These impulse currents are a special class of transients. Inasmuch as they are a sub-class of the general transient, they are included in the general equation of my previous paper, but they were not specifically treated.

They apply to a circuit, or a section of the circuit, of uniform constants, but the case which Prof. Pupin discussed, where the circuit constants change, is treated in general in my previous paper under the term "Complex Circuits." It is more particularly treated in that section in my book on "Transient Phenomena," which discusses the transition points between different circuit sections of different constants, as lines, transformers, etc. It is very interesting to note the effect on such a circuit of the transients existing; there is an energy exchange between the different circuit sections, the energy being dissipated in some sections at a rate higher than the average, and in other sections at a rate lower than the average,—there is energy transferred, taken from one section and delivered at another section.

With regard to mutally inductive circuits, even these may be considered under the general equation, by suitable terminal conditions, and effective values of r, g, L, C.

I may say that the circuit as described by Mr. Lippelt is in industrial existence. It is the circuit of the multi-gap lightning arrester.

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THE MUNICIPALLY-OPERATED ELECTRICAL UTILITIES OF WESTERN CANADA

BY A. G. CHRISTIE

ABSTRACT OF PAPER

The paper discusses a number of public utilities in various cities in Western Canada where practically all public utilities are municipally owned and operated. The characteristics of these cities are reviewed and a brief outline of equipments of the various plants is given. The costs and methods of financing these utilities are discussed at considerable length and the charges for various services are summarized. While the paper is not to be regarded as an endorsement of public ownership, the author finds that these utilities on the whole have been conservatively managed and have been practically free from political influence.

WHEN municipally-owned public utilities are discussed in the United States, it is generally held that these are open to the following criticisms:

1. The plant is not kept modern and up-to-date, resulting in indifferent service.
2. Rates are high in consequence of the preceding conditions.
3. The utility's finances are often poorly managed and frequently mixed with other city accounts.
4. The organization is indifferent and without definite lines of authority.
5. Politics are usually a factor in both organization and operation.

Mr. Halford Erickson of the Railroad Commission of Wisconsin has expressed very concisely the American point of view in regard to municipally-owned utilities, in a paper on "State and Local Regulation," an extract of which follows:

> "Such utilities furnish no better service than privately owned or operated utilities. In fact, it is often a great deal worse. Municipalities are as a rule slow in responding to new discoveries and improved methods and they often fail to properly list and supervise their meters and other equipment. Examination of the inspector's reports, at least in our state, reveals the fact that while some municipalities provide good service, the service in a greater proportion of them is, on the whole, on a lower level than is the case of privately-operated plants.

"When it comes to rates the situation for municipally-operated utilities is no better. When the Commission first entered upon its duties, it found the state literally streaked with unjust discriminations which were as flagrant in municipally-operated as in privately-operated plants. While these discriminations have now been largely done away with, the task of wiping them out was also fully as great for the former class of plants as for the latter. The same is also true when it comes to establishing and maintaining equitable rates. While the rates charged by the municipally-operated plants are often relatively low, this is not often due to a low cost of production of the service, but largely because in one way or another upkeep and other costs are shifted from the consumer as such to the taxpayer as such."

Practically all public utilities in the cities of the Western Canadian provinces are municipally owned and operated. An investigation into the municipal activities of the cities of this section to determine to what extent the above criticisms in reference to public ownership could be applied to them, should aid materially in presenting new facts in the discussion of public ownership. After a study extending over four years, an inquiry was made during the summer of 1915 into the municipally-owned electric light and power utilities of these cities.

The electric light and power utility was chosen because it was one of the first to be established and is also one with which comparisons can be made with privately owned systems. It has become better organized and established than some of the other civic undertakings and the early mistakes in its management are now apparent. Its organization is also more extensive than later utilities. Hence for the reasons just stated, its production costs and physical equipment would probably show any inefficient or incompetent administration under municipal ownership better than other more recent ventures in civic control. The investigation was intended to cover certain social and economic phases of municipal ownership as well as its technical aspects. Hence the character of the people and their cities will be discussed together with the administration, organization, financing, physical equipment and rates of the municipal electric light and power departments.

SOCIAL CONSIDERATIONS

It would be a very difficult matter indeed to differentiate between the people of the various cities under discussion, but as a class they have some distinct characteristics. In the first place the Canadian West is a "young man's country." The residents of the cities generally came west as young men and have seen the country develop. All are optimistic and boosters of the West in general and of their own locality in particular. They have learned to cooperate in many lines, such as boosting real estate ventures, etc., and this has had a very marked effect on the conduct of municipal affairs. In fact this spirit of cooperation is the real basis of the success of their municipal ownership ventures. The cities that have not developed this spirit to the fullest extent are those that have had troubles with politics and local interference in the administration of their utilities.

The people of these Western cities were the restless and ambitious elements of the United States, Eastern Canada, the British Isles and foreign countries. The British sentiment is very strong and carries with it the imported ideas of municipal ownership. The readiness of the Canadian and American elements to try any new system that appeared reasonable and promising, accounts for the early acceptance of these principles of civic control and operation. Another characteristic that is peculiar to the West is the general lack of class distinctions.

This democratic condition has resulted in a better mutual understanding and a wider range of interests between all members of the community. Political machines are harder to build up under such conditions and there has apparently been less keen competition for positions in civil employ. The fixed compensation in such work appeals less to the average individual than the gambling chances of other classes of business.

CHARACTERISTICS OF THE CITIES AND THEIR UTILITIES

Manitoba, Alberta and Saskatchewan are primarily agricultural provinces at the present time, although the great natural resources in water power, coal, oil, gas, asphalt and iron will undoubtedly lead to great industrial development in Alberta in the near future. Of late years the urban population of these states has grown faster than that of the country districts. A partial crop failure in 1914 and the war depression brought this unnatural condition very forcibly to the attention of the people and as a result there has since been a steady trend back to the land.

British Columbia on the other hand is a land of high mountains, rolling plateaus and very fertile valleys. Its interests vary from fruit raising, ranching and other agricultural pursuits to lumbering, mining and fishing. Undoubtedly great mineral wealth will be developed in the future although at present much of the country has not been prospected or opened up. The electrical utilities of the two largest cities, Vancouver and Victoria, are privately owned. Only one of the cities having municipal plants was investigated.

The outbreak of the European war proved a hard blow to Western Canada. Not only have tens of thousands of the best fitted young men gone to the front, but the money in the country has been diverted from local development to war purposes. The closing of the European money markets has cut off for the time being any borrowing for future development. This situation has resulted in a complete tying-up of all industry and commerce. The present financial stringency will, however, be relieved in a measure when the large crops of 1915 are marketed.

Comparatively few manufacturing industries have been established in the West. Those in operation either handle agricultural or sea products, such as in packing plants, flour mills, food product plants, fish canneries, etc., or supply the rural needs by lumber mills, cement plants, brick works and agricultural machinery shops. In the natural gas district around Medicine Hat, metal-working industries such as machine shops, brass foundries, rolling mills and also glass works, have been started and will no doubt expand with the growth of the country.

The cities selected are the larger ones of the Western provinces These have been characterized by extremely rapid growth within the last fourteen years, as shown by Table I. At the same time they have been exploited by real estate speculators until land values became greatly inflated in 1914. This resulted in a financial collapse just before the war broke out

An example of this exploitation is to be found in extensions of the municipal street railways which were frequently made under political pressure from the land speculators. Generally such extensions have not paid for themselves and are now a source of considerable loss to the city. Each city council has had full power to undertake such expense and in boom times the people allowed them to do so. It would seem advisable to have some provincial executive board independent of the city's governing body which would have authority to restrain such needless exploitation and to act as a brake on too-confident municipal administrations.

Brief outlines of the characteristics of each of the cities con sidered and of the history of their municipal electric plants will be given in the following paragraphs.

Regina is the capital of Saskatchewan and as such will always be a city of importance. Its growth has been more steady than that of other Western cities and it is built up with fewer outlying subdivisions. This consolidated condition makes it an easy city to serve with electric light and power, but a poor city for financially successful street car operation. It has no manufacturing industries of any consequence.

The city first built a power plant in 1904. Additions were made to this old plant from time to time until 1914 when its undesirable location making further extension inadvisable, a new plant was built. This new station will take care of all future growth for many years. The fixed charges on the old and new plants form a considerable item in the cost of electricity. The increased operating economy of the new plant will, however, practically offset the increased fixed charges. This economy will become more appreciable as the plant increases its output.

TABLE I.—DATA ON SIZE OF CITIES.

City.	Estimated present population	Population as per 1911 census.	Population as per 1901 census.
Kamloops, B. C.	5,500		
Medicine Hat, Al'ta	9,000	5,603	1,570
Lethbridge, Al'ta	10,000	8,050	2,072
Moose Jaw, Sask	20,000	13,823	1,558
Saskatoon, Sask	25,000	12,004	113
Regina, Sask.	40,000	30,213	2,249
Edmonton, Al'ta	50,000	24,900	2,626
Calgary, Al'ta	80,000	43,704	4,392
Winnipeg, Man	200,000	128,157	42,340

Saskatoon is the leading city of central Saskatchewan and is the seat of the Provincial University. It is a large distributing center and also has large mills producing food products.

Its first municipal station was started in 1908. On account of the city's growth, this was superseded in 1911 by a new plant. But in this plant too, proper provision was not made for the rapid growth of the city and as a result it has been necessary to replace reciprocating engines by steam turbines of greater capacity. The present plant is well situated and is now equipped for economical operation, but is somewhat handicapped by extremely high coal costs due to freight rates on the long haul from the Alberta mines.

Moose Jaw has always been a railway town, the Canadian Pacific Railway having maintained large car shops at this point for many years. Its other industries include flour mills, a packing plant, etc.

The city undertook the production of electric power in 1904. The power plant was burnt down about 1912 and was a total loss. Afterwards a new plant was built on the same site. This additional expenditure has serious effects on the city's finances and as a result the new plant was not fully equipped when war broke out. The plant is well laid out and when finished should give good service.

These Saskatchewan cities are all in prairie country and have no nearby available supplies of water power, cheap high-grade coal, or natural gas. A private corporation has recently proposed to pipe natural gas to them from the Alberta gas fields. The city of Regina has made an agreement with this company to buy the gas at wholesale at the city limits and will sell it to customers from a municipally-owned and operated distribution system, which the city will install. Meanwhile all power must be derived from coal brought either from Alberta or from the Great Lakes. It therefore seems improbable that they will become great industrial centers in the near future. Their further growth will depend then on their natural development as distributing centers.

With neither water power or cheap coal at hand, it is probable that few attempts will be made to transfer their public utility power loads to private corporations. Quite recently, however, a suggestion was made to supply them with electric power derived from low-grade lignite coals which occur in large quantities in the southern section of the province and are an extension of the North Dakota fields. Even in case such a project is successfully completed, it is probable that the cities would buy the power at wholesale rates at a local terminal station and continue as before to sell it to customers from their own distribution system, retaining their present municipal plants as reserves.

In contrast to those of Saskatchewan, the cities of Alberta have large coal fields near at hand, while Calgary has also cheap water-power. It is therefore natural to expect considerable industrial development in these cities in the near future.

Medicine Hat, besides having coal deposits practically under the city, is located in the center of the most extensive of the Alberta natural gas fields. It is thus assured an ample supply of cheap fuel. Although built in the rolling, dry belt of Alberta, the presence of the natural gas has resulted in a more rapid industrial growth in this city and surrounding towns than in any other city in the West. Reference has already been made to several of these plants.

Natural gas is used throughout the city for all domestic purposes such as heating, cooking and largely for lighting as well. It is also used for street lighting. The success of a municipal electrical plant under such conditions was therefore doubtful and it was not decided to build such a plant until 1911. At first a gas engine plant was installed, but in November 1913 a new steam turbine plant was put in operation and took the load formerly carried by the gas engines. This change was made largely on account of the high first costs and repair charges on the gas engines, which resulted in high power costs. A very simple plant was installed without superheaters or economizers, for the gas used under the boilers was supplied by the city's own wells at a very low cost.

The demand for power for industrial purposes developed very rapidly until war broke out. It is probable that this demand will increase again with the re-adjustment of conditions after the war.

Lethbridge in Southwestern Alberta is the center of an extensive colliery district and serves as a distributing point for the surrounding towns. Although well supplied with coal and natural gas it has not developed any industries except those connected with mining. All the collieries have their own plants.

The city bought out the electrical plant of a private company in 1908. This plant was uneconomical in operation and poorly located. Work was started at once on a new plant. The old station burnt down in December 1909 just before the new plant was complete. The location of the new station, while favorable for operation, was such that construction costs were excessive and in consequence the plant has high fixed charges.

The municipality owns and operates its own coal mine on leased land adjacent to the plant. On this account it has the cheapest coal supply of any city in the West.

Edmonton is the capital of the Province of Alberta and is the location of the new Provincial University. It embraces about 56 square miles within its boundaries as a result of real estate exploitation. Its industrial works consist principally of two packing houses, lumber mills, flour mills, brick yards, etc. It is expected that the great undeveloped sections of Northern Alberta will contribute largely to the future prosperity of this city as it is the natural outlet for the whole north country.

There are seams of lignite coal under the city itself, while higher grade coal occurs in great quantities to the west of the city. Several undeveloped water power sites in the neighboring country are available for power development.

Edmonton's municipal power plants have had interesting histories. The first electric station and pumping plant was built on the banks of the North Saskatchewan River apparently with no consideration of future developments. This plant soon reached its maximum capacity and a producer gas power plant was installed in an adjoining building to furnish additional electric power. A separate pumping station was next built a short distance from the old plant. It was provided with its own boilers and with a vertical reciprocating pumping engine placed in a pit. In a few years another steam power plant was erected beside the producer gas building with reciprocating engines and hand-fired boilers. Later this was extended and steam turbines and boilers with mechanical stokers were installed, several steam engines were scrapped, and the original station definitely abandoned. In the meantime the pumping plant was enlarged and the vertical reciprocating pumping unit was scrapped in favor of centrifugal pumps. At present the steam required by the pumping engines is supplied from the main boiler plant through a tunnel and the pumping plant boilers are permanently closed down. When Edmonton absorbed the town of Strathcona on the opposite side of the river, its electric plant and pumping station were also taken over. These operated non-condensing and were therefore uneconomical in operation. The Strathcona plant was closed up as soon as the water and electrical services could be assumed by the Edmonton station. It can thus be seen that the present municipal plant is somewhat of a makeshift. Contracts were let over a year ago for the construction of a complete new power house. But the war made necessary the postponement of these contracts. At the time of this investigation the city was considering the purchase of power from private corporations. Some of these were hydroelectric proposals, others were from coal companies who proposed to generate power at their mines and transmit it to the city.

Calgary in Central Alberta is the leading city of the middle west. It appears to have sustained less crippling of business during the war depression than any of the other cities. On account of cheap water power, available nearby coal fields and its supply of natural gas, it is developing into an important industrial center. Among its principal industries are the big Ogden car shops of the Canadian Pacific Railway, a cement mill, a packing plant, soap works, lumber mills, flour and food product mills, etc.

Calgary started its first municipal plant in 1905 and kept adding to it until 1911 when a new plant, in a more favorable location, was put in service. About the same time a private corporation, the Calgary Power Co., which now has 31,500 h.p. available in its two hydroelectric stations, entered into a contract with the city to supply it with power up to 8000 h.p. But on account of low water at the time of the winter peak loads, the city has had to maintain its plant at a capacity capable of carrying the full load in an emergency. The fixed charges on this steam plant now form a considerable proportion of the cost of power.

A private corporation, the Eau Claire & Bow River Lumber Company, serves customers in the central part of the city with electricity partly derived from water power and partly from a steam plant. This company had a franchise previous to the establishment of the municipal plant. Another private company has a franchise to supply natural gas for domestic purposes at a cost of 35 cents per 1000 cubic feet. Much domestic lighting is done with gas. Hence the load on the municipal plant is not so large as would be the case if it had a monopoly of the lighting business as in other cities.

Half of the boilers in the municipal plant are fired by gas of 1000 B.t.u. per cubic foot and costing 15 cents per 1000 cubic feet. The others burn coal. The plant is well designed and well equipped and when in continuous operation produces very cheap power.

At present an agreement for one year is in force between the city and the Calgary Power Company whereby the latter supplies the full city demands for power at a low figure and has the use of the municipal steam plant for emergencies. The Calgary Power Co. pays all operating and maintenance costs at the municipal plant, which is still handled by the regular city operating staff. The company does not, however, pay any of the plant's fixed charges.

The steam plant is arranged for ample future development. At the present time, several additional hydroelectric proposals are receiving consideration. With an abundant supply of cheap water power further additions to the steam plant may become unnecessary.

Winnipeg is the largest city in all Western Canada, and being the outlet to the east of all the western railroads, it has great future possibilities.

A private corporation, the Winnipeg Street Railway Co., had a franchise to furnish electric power and operate street railways very early in the history of the city. Up to 1907 this company charged 20 cents per kw-hr. for lighting. In that year it put into operation its hydroelectric plant at Lac du Bonnet and reduced the rate to 10 cents per kw-hr.

In the meantime the citizens recognized that only by having a supply of very cheap power could they hope to see Winnipeg become an industrial center and they voted money in 1906 for building a municipal hydroelectric plant which was completed and put in operation in 1911. The rates quoted to its customers were much below the former prices of the railway company. In 1914 the municipal plant at Point du Bois had a generating capacity of 22,500 h.p. which has since been increased to 50,000 h.p. The total power available at this plant is 100,000 h.p. The design and operation of this plant have received much attention in the technical press and will not be described here.

Kamloops was the only city in which inquiries were made in British Columbia. It is located at the junction of the North and South Thompson Rivers in the central section of the province. Kamloops is a divisional point on two transcontinental railroads. The surrounding country is a rich agricultural and fruit district. Some mining is carried on in adjacent sections and it is probable that this industry will increase in importance as the country develops.

The city's first municipal plant was built about 1907. Owing to the rapid growth of Kamloops this plant proved inadequate and a new municipal electric plant of 1200-kw. capacity was built in 1912 together with a new pumping plant on a site east of the city where an excellent water supply was available from the South Thompson River. But owing to the high price of fuel, it was decided to develop a hydroelectric site at Barriere about 18 miles north of the city. Unexpected difficulties were encountered in the construction of this plant and it was not put in service till the beginning of 1915. It has a capacity of 1500 kw. which can be increased later as the load builds up. The transmission line to the city carries 44,000 volts with a step-down transformer station at the steam plant. The cost of this hydroelectric system far exceeded the original estimates and the steam plant is still held as a relay, consequently the electric service of the city has to bear very high fixed charges due to these two plants.

Other utilities owned by the various cities and some general information regarding them is given in Table II. Besides those undertakings given in the table, practically all maintain municipal hospitals.

ORGANIZATION OF UTILITIES

The organization of the municipal governments varies somewhat in the different cities. However, it is generally the practise to have three commissioners in charge respectively of Finance, Utilities, and Public Works and Welfare.

In some cases these are elected by the people and in other cases are appointed by the city's common council. At Lethbridge the public utility commissioner acts as superintendent of the electric light and power department and of the street railway system. Generally, however, a superintendent is provided for each utility. In the case of Calgary and Edmonton, the city's electrical engineer takes charge of the distribution of the current from the plant's switchboard.

In general the superintendents of these municipal utilities are capable men and are exerting as much energy to secure economical results as if they were employed by private corporations. Most of them have held their positions for a considerable length of time and have virtually developed and built up their utilities. These executives are not likely to be subject in municipal service to as much pressure and driving from high officials as in the case of superintendents with private concerns. Hence their success is largely a measure of their own personal initiative.

All the provinces have very stringent boiler inspection and engineer's licensing laws, and as a result, the operating engi-

TABLE II.—DATA ON PUBLIC UTILITIES.

City	Electric light and power	Electric street railway	Water works	Sewage	Gas	Other utilities	Source of water supply
Kamloops, B. C....	Municipal	None	Municipal	Municipal	None	....	South Thompson R.
Medicine Hat.....	Municipal	None	Municipal	Municipal	Municipal	....	South Saskatchewan R
Lethbridge.........	Municipal	Municipal	Municipal	Municipal	Private Corporation	Coal Mine	Belly River
Moose Jaw.........	Municipal	Private Corporation	Municipal	Municipal	None	Cemetery	Local Creek
Saskatoon..........	Municipal	Municipal	Municipal	Municipal	None	Cemetery	South Saskatchewan R.
Regina.............	Municipal	Municipal	Municipal	Municipal	None	Stock Yards	Lake Wascawa
Edmonton..........	Municipal	Municipal	Municipal	Municipal	None	....	North Saskatchewan R.
Calgary............	Municipal	Municipal	Municipal	Municipal	Private Corporation	....	Elbow River
Winnipeg..........	Municipal	Private Corporation	Municipal	Municipal	Private Corporation	....	Hydro Plant Winnipeg River.

neers in the various plants are all high grade men. The firemen, as a rule, are men working up for a license and consequently take an interest in their plant and in their work. Such operating forces should be able to give the superintendents valuable aid in obtaining economical results.

In only one case did there seem at present to be any politics in the organization of the plant. This city, however, has had a long record of political and civic-council interference with the operation of its utilities, greatly to their detriment. Another city is said to have had similar experience in the past but seems to have overcome these evils at the present time. Considerable criticism was heard in Edmonton in regard to the operation of the city's municipal street railway system. Its employees had formed a union and were said to dominate the management of the system through their political influence. An attempt was being made at the time of this investigation to drag the municipal street railway system of Calgary into politics. This utility has up to the present time been the most successful civic tramway in the West and holds a record for good service and competent management.

No civil service laws are in force other than the necessary licensing of engineers. The superintendent engages and discharges the men under him and generally promotes his own men as openings occur and the men have the necessary legal and administrative qualifications.

It has been urged against municipal ownership that more men are employed than would be the case in private plants. In those cities where politicians are said to have interfered with the utilities there seemed to be some evidence of an excess of men, and a laxity of discipline. But in the other cities the plants appeared to have the minimum number of men necessary to properly carry on operation. The new municipal plant at Regina is a striking example of careful layout and operation to reduce labor to a minimum, as very few men are needed to run this station.

Another interesting fact is that almost all plant employees are under middle age. One may partly account for this condition by the use of recently developed machinery to which the older men have not adapted themselves.

A very necessary factor for obtaining efficiency in planning and operating a utility, is continuity of management. If a spoils system exists in municipal politics one cannot expect the city's public utilities to be either well managed or suitably equipped. The spoils system as generally understood does not seem to exist in any of these cities. On the other hand Edmonton has suffered severely from too frequent changes in the management of its utilities. The new man coming in was usually forced to complete work unfinished by his predecessor and with which often he was not fully in sympathy. Then he also was liable to removal before he had his plans for improvement fully carried out. This has resulted in the heterogeneous assortment of equipment and the odd station lay-out already described.

POWER PLANTS AND EQUIPMENT

All of these cities as shown in Table I have grown very rapidly in a very short period. This rate of growth could hardly be foreseen in any particular city for other towns equally favored did not develop so rapidly. Hence much of the earlier plant equipment due to small size and poor operating economy has become obsolete. There has, therefore, been in each city a rebuilding of old plants and the construction of new plants as noted in preceding paragraphs.

The power plant buildings in most cities are of the usual construction with steel framing and brick walls with the usual arrangements for lighting, ventilation and traveling cranes. Regina's plant, however, is an exception. Here the city went to considerable expense to make its new plant conform with the general plan of buildings to be erected on the adjoining Governmental reserve. Saskatoon's plant also shows a considerable amount of architectural taste.

Table III gives some general data on the equipment of the various plants. All have standard B. & W. water-tube boilers equipped with superheaters except in the cases of Medicine Hat and Kamloops. Induced draft fan equipments are used everywhere except in Kamloops. At Regina forced draft fans are also used in connection with the mechanical stokers. At Edmonton an "évasé" or Venturi form of induced draft stack is used, where a 20-h.p. motor drives the fan necessary to serve 2000 b.h.p. The Kamloops plant has a six-ft. concrete chimney 185 ft. high.

A question arises as to whether a chimney and natural draft would not be more economical in some cases. At Regina on account of the proximity of the Parliament Buildings and Park, a chimney was not permitted. In several cases the

TABLE III.—STEAM PLANT EQUIPMENT.

City	Generator capacity	Boiler capacity	Economizers	Main engine equipment.
Kamloops	1,200 kw.	4 Boilers 1000 h. p.	None	2— 600 kw. Curtis Turbines.
Medicine Hat	3,000 kw.	4 Boilers 1600 h. p.	None	2— 750 kw. Curtis-Rateau Turbines. 1—1500 kw. Curtis-Parsons Turbine.
Lethbridge	2,300 kw. 2 phase	8 Boilers 2260 h. p.	1-Green 1-Sturtevant	1— 300 kw. Compound H. S. Engine. 1— 500 kw. Triple Expansion H. S. Engine. 1—1500 kw. Curtis-Parsons Turbine.
Moose Jaw	3,000 kw.	8 Boilers 2600 h. p.	Sturtevant	1— 500 kw. Curtis Turbine. 1—1000 kw. Curtis Turbine. 1—1500 kw. Curtis-Parsons Turbine.
Saskatoon	5,950 kw. 2 phase	8 Boilers 4000 h. p.	Green	1— 750 kw. Compound Corliss Engine. 1—2000 kw. Parsons Turbine. 1—3250 kw. Parsons Turbine.
Regina	7,600 kw.	Old Plant 4 Boilers 1600 h. p. New Plant 8 Boilers 2600 h. p.	Sturtevant	1— 300 kw. Corliss Engine. 2— 400 kw. D. C. Engine Units. 1— 500 kw. L. P. Parsons Turbine. 2—1500 kw. Curtis-Parsons Turbines. 1—3000 kw. Curtis-Parsons Turbine.
Edmonton	10,250 kw.	16 Boilers 7000 h. p.	None	2— 400 kw. D. C. Compound Engines. 1— 750 kw. D. C. Triple Expansion Engine. 1— 700 kw. Producer Gas Engine. 1—1000 kw. Compound Corliss Engine. 1—1000 kw. Parsons Turbine. 1—2000 kw. Curtis-Parsons Turbine. 1—4000 kw. Curtis-Parsons Turbine.
Calgary	11,350 kw.	16 Boilers 5430 h. p.	None	1— 600 kw. Triple Expansion Engine. 1— 500 kw. Triple Expansion Engine. 1— 750 kw. Compound Corliss Engine. 1—2000 kw. Parsons Turbine. 1—2500 kw. Curtis-Rateau Turbine. 1—5000 kw. Parsons Turbine.

power plants are located beside rivers in the bottom lands under the bluffs and it was feared this might prevent a chimney from providing draft unless of excessive height. In general, however, it is claimed that radial brick and concrete chimneys were too expensive to commercially compete with the induced draft plants.

Underfeed stokers are giving good satisfaction at Regina. Natural gas is burned in Gwynne burners in Medicine Hat's plant and in part of the Calgary station Chain grate stokers are in use in all other plants except Kamloops. Hand fired grates were installed at Kamloops where wooden slabs from the lumber mills are burned part of the time as fuel.

Coal and ashes are almost universally handled by bucket conveyers. The coal is stored in elevated bins above the firing aisle. The ashes are elevated into storage bins convenient for loading railroad cars. Most plants are now provided with equipment for analyzing and testing their coal. Several practically buy coal on the heat unit basis. Economizers are used where coal is expensive and therefore when full utilization of heat is of first importance.

In the newest installations there is a decided tendency towards motor drives for all auxiliaries.

Admiralty-type feed pumps are installed in many plants though the simple turbine-driven centrifugal boiler feed pumps have been used in two cases.

The waters of Western Canada generally contain scale forming salts which make them unsuitable for boiler feed. However, there is no uniformity of treatment of the feed water. Some plants soften it while others use boiler compounds. All use feed water heaters. The condensate from the surface condensers is returned to the boilers in every station.

The adoption and use of instruments to increase boiler room economy is universal. Coal as a rule is automatically weighed and recorded. Gas burned under boilers is metered. The boiler feed water is generally measured by V-notch recorders which have universally given good satisfaction. Venturi meters are employed in some plants. CO_2 recorders are in use in almost all plants. Steam flow meters have been installed in a few cases. Many plants are equipped for making complete tests and these are carried out at regular intervals either to determine the best coal to use, or to learn the most economical methods of operation.

The older generating equipment consisted of steam engines, usually of the vertical high speed or Corliss types. Steam turbines have been provided in all recent installations. It is interesting to note in Table III the predominance of Parsons and Curtis-Parsons units. The number of British machines is also a striking feature. Recent purchases indicate an increasing preference for European machinery. The preferential tariff to the British Isles has something to do with this condition, though the most recent order—a 6000-kw. turbo-generator for Edmonton, was taken by a Swiss company.

Usually the condensers are supplied by the party that furnishes the main turbine. These are all of the surface type and give little trouble from tube failures with the cooling water used. All foreign condensers are provided with vacuum augmentors of various types and are usually supplied with three-throw motor-driven air pumps, which maintain high vacuum.

In electrical machinery, the use of European equipment is even more noticeable than in the case of the engines and turbines. The switchboards with one exception are of American manufacture and have been built according to modern practise.

All the larger plants are provided with some machine tools to enable them to make their own repairs. Fine toilet rooms, wash rooms and lockers have been provided in many stations for the men.

In Saskatoon, on the initiative of the superintendent, a society for mutual improvement along technical lines was formed among the utility's employees. Apparently this has not been attempted in other places and outside of local engineering societies there seems to be no organized effort to educate the men in technical subjects.

The Winnipeg plant, being hydroelectric, is not included in the preceding general statements. The plant is built on the Winnipeg River, 77 miles from the city. The power is carried into town over a high-tension transmission system. During construction it was necessary to build an electric tramway to the plant to convey the needed materials and machinery. This is still retained and operated by the city.

On the basis of these facts it may be stated that as a whole the municipal power plants of these cities are up-to-date in the matter of physical equipment, though often retaining some of the older units as reserve. They are also provided with competent staff and modern instruments to ensure efficient operation and low unit production costs.

DISTRIBUTION SYSTEMS

In considering distribution systems, it must be remembered that the cities are new and are scattered over large areas. This in a measure simplified wiring problems although provisions for future growth have made necessary many underloaded circuits and transformers. In those cities where the total output is metered the distribution losses run from ten to eighteen per cent of the current generated.

The consulting engineers who were employed in laying out the first plants of several of these cities insisted on two-phase alternating-current systems. Most plants have been entirely changed over to three-phase, but at least two cities are still operating with two-phase machinery and distribution systems involving unnecessarily high first costs and maintenance charges.

Distribution systems are generally at 2300 volts except in some cases where 6600 volts is carried to substations. The use of 2300-volt motors for power service is increasing. The starting devices used with these motors are more complicated than with lower voltages, but being without transformers, the net efficiency of the service is higher.

In two cities the distribution system is in charge of an electrical engineer and is independent of the power plant superintendent. In general, however, the whole electric light and power utility is under the supervision of one man and this seems to be the more desirable and more efficient condition.

COST AND FINANCING OF UTILITIES

All of these utilities are financed by loans on municipal debentures whose terms vary from 20 to 35 years and longer, and bearing interest at rates of 4 to 6 per cent. Most of these were marketed in Great Britain, though a few were placed in Eastern Canada and in the United States. The expansion of Western Canada was so rapid before the war, that fears were expressed in financial circles that these cities were exceeding their ability to meet these obligations. Hence recent debenture issues have had to bear higher interest than earlier ones on this account. The war, however, has closed all money markets and the West, being without funds to carry on development, has felt the resulting depression much more keenly than the East.

The municipalities provide for the retirement of these debentures by the maintenance of sinking funds. Interest and sinking fund charges must be met out of the current revenue of the utility and in general, rates are adjusted to produce these funds together with a small surplus for emergencies.

An attempt has been made in Tables IV and V to summarize the financial statements for the year 1914 of the various utilities discussed. In every case possible the auditor's statements were used as a basis for the analysis. The kilowatt rating of the plants is that of the machinery available for service. The plant value per kilowatt capacity in Table V seems high in several cases. This usually covers obsolete machinery still carried on the books, together with the costs of errors and mistakes made in building up the plant from a small station. The power output of the plant in kilowatt-hours was used as the basis for the figures in Table V which shows all costs on a kilowatt-hour basis. Table V also includes average figures in nineteen Massachusetts steam power plants for 1914, based on the returns of the companies to the Board of Gas and Electric Light Commissioners of that state.

In connection with the high first costs of the distribution systems and the yearly distribution costs, attention is drawn to the fact that these cities have grown up with homes scattered over large areas. The municipal utility has had to supply all reasonable demands for light and power even in the most outlying districts. This has resulted in high pole and line expense and correspondingly high upkeep charges.

The capital cost for the hydroelectric plant at Kamloops has been so great that its fixed charges will nearly equal the former cost of fuel in the steam plant. But the labor cost will be less than before. Hence the net cost of power will not be appreciably decreased by the use of hydroelectric power unless the load factor of the plant can be greatly increased. Efforts are being made to secure additional mining and irrigation loads.

It has been said that the electrical utility at Medicine Hat does not pay enough for the gas that it consumes and that if it were charged the same rates as other consumers, the surplus would be wiped out and higher rates might even be necessary.

In the Moose Jaw statement in Table IV, a deduction of $9,012.00 is made from the total cost. This covers the charges for operating the city pumping station which is connected with the electric plant and operated by the same force. Hence for purposes of comparison in Table V, this cost was deducted

TABLE IV.—SUMMARY FROM 1914 FINANCIAL STATEMENTS.

	Kamloops	Medicine Hat	Lethbridge	Moose Jaw	Saskatoon	Regina	Edmonton	Calgary	Winnipeg
Present population	5500	9000	10,000	20,000	25,000	40,000	50,000	80,000	200,000
Rated kw. of plant	2700	3000	2300	3,000	5,950	7,600	10,250	11,350	30,000
Total debenture issue	$506,500.00	$430,000.00	$689,665.73	$707,852.39	$1,047,665.10	$1,486,333.34	$2,830,190.99	$2,029,202.28	$7,412,000.00
Value of plant	$502,693.49	$368,142.89	$456,370.78	$354,071.30	$570,000.00	$704,464.20	$1,955,091.06	$976,287.09	$3,962,144.49
Value of distributing system			$139,757.37	$190,446.68	$430,000.00	$625,031.61	$745,985.94	$1,188,921.37	$2,904,779.09
Kw-hours generated	2,628,100	3,050,070	3,415,000	3,739,990	8,873,642	9,315,355	21,927,089	31,391,596	62,493,162
Kw-hours metered	2,338,912	......	......	3,031,246	7,966,920	8,223,895	......	......	......
Net revenue	$84,692.89	$49,251.08	$110,898.53	$179,428.26	$340,628.08	$326,435.73	$767,870.71	$670,512.24	$976,347.50
Cost of coal	$4.90	(Natural Gas)	$1.20	$3.40	$6.66	$5.40	$3.22	(Gas and Water Power)	(Water Power)
Operating Costs									
Fuel	$35,271.92	$1,000.00	$12,562.55	$53,624.12	$121,296.68	$131,565.43	$165,238.86	$48,735.17	......
Wages	13,951.78	12,721.98	14,953.84	21,531.98	28,972.22	41,023.17	78,619.25	32,056.20	$41,330.32
Water	......		720.00	1,698.25	2,605.71	824.48	1,538.40	5,048.00	......
Oil, waste, supplies etc.	1,094.01		2,452.76	5,257.74	3,950.73	5,509.54	7,272.25		8,538.79
Repairs and maintenance	98.26		7,627.23		11,541.90	10,549.25	56,919.81	11,732.74	29,621.02
Distribution Costs									
Wages	1,804.17	3,350.87	1,357.05	9,941.24	17,505.59	4,703.30	34,739.23	80,648.89	8,552.96
Repairs and maintenance			7,314.77	11,450.95		14,594.73			36,786.47
Miscellaneous	......	135.41	......	3,183.94	......	4,425.93	7,403.57	166,075.84	109,532.18
Overhead Costs									
Salaries	4,012.95	3,593.25	5,529.44	2,475.00	19,424.56	14,482.53	41,722.66	71,379.48	55,290.00
Office expenses	375.97		2,767.85	8,218.34			6,208.99		34,041.16
Insurance	603.47	......	575.92	1,001.14		2,324.70	1,949.45	3,224.52	182.20
Taxes	......	......	8,114.67	1,028.95	......	......	4,824.68	8,675.24	4,007.05
Employers liability insurance	......	......	514.65	1,578.34	......	......	......	......	......
Fixed Charges									
Interest	10,225.20	14,821.95	30,071.15	29,704.47	45,690.22	63,107.93	175,063.84	93,339.97	305,526.11
Sinking funds	4,147.80	13,004.26	16,069.72	......	20,983.77			35,612.94	......
Depreciation	......	......	......	24,865.13	29,967.76	19,370.65	106,606.82	36,125.29	264,254.52
Total Cost				175,559.59		311,481.64			
Less deductions				9,012.00		7,001.62			
Net cost	71,585.53	48,627.72	110,631.60	166,547.59	302,029.14	304,480.02	688,107.81	592,654.28	897,662.78
Surplus	13,107.36	623.36	266.93	12,880.77	38,598.94	21,955.71	79,762.90	77,857.96	78,684.72

TABLE V.—COSTS PER KW-HOUR GENERATED, 1914.

	Kamloops	Medicine Hat	Lethbridge	Moose Jaw	Saskatoon	Regina	Edmonton	Calgary	Winnipeg	Average of 19 Mass. Cities.
Present population	5,500	9,000	10,000	20,000	25,000	40,000	50,000	80,000	200,000	66,700
Rated kw. of plant	2,700	3,000	2,200	3,000	5,950	7,600	10,250	11,350	30,000	7,530
Kw-hours, generated	2,628,100	3,050,700	3,415,000	3,739,990	9,716,142	9,315,355	21,927,089	31,391,596	62,493,162	11,010,000
Cost of coal	$4.90	(Natural Gas)	$1.20	$3.40	$6.66	$5.40	$3.22	(Gas & Water Power)	(Water Power)	$3.65
Plant cost per kw. capacity	187.59	122.71	198.42	118.02	95.80	92.70	190.75	86.01	132.07	....
Distribution system cost per kw.			60.76	63.48	72.27	82.25	72.80	104.75	96.82	....
Net Revenue per kw-hour	3.222c.	1.612c.	3.247c.	4.797c.	3.838c.	3.504c.	3.504c.	2.136c.	1.562c.	....
Operating Costs										
Fuel	1.342c.	0.033c.	0.369c.	1.298c.	1.367c.	1.412c.	0.754c.	....	....	0.570
Wages	0.531	0.417	0.438	0.527	0.326	0.440	0.358	....	0.066	0.216
Water	....		0.021	0.045	0.029	0.009	0.007	....	....	0.022
Oil, waste and supplies	0.041		0.071	0.140	0.045	0.046	0.033	....	0.014	0.008
Repairs and maintenance	0.004		0.223		0.130	0.087	0.260	....	0.047	0.092
Total Operating Cost	1.918	0.450	1.122	2.010	1.897	1.994	1.412	....	0.127	0.908
Distribution Costs										
Wages	0.069	0.109	0.040	0.266	0.199	0.051	0.158	....	0.014	0.198
Repairs and maintenance			0.214	0.306		0.121		....	0.059	0.225
Miscellaneous	....	0.004	....	0.085	....	0.047	0.034	....	0.175	0.147
Overhead Costs										
Salaries	0.153	0.117	0.162	0.066	0.219	0.156	0.191	....	0.088	0.344
Office expenses	0.014		0.081	0.226			0.028	....	0.055	
Insurance	0.023	....	0.017	0.027	....	0.025	0.009	....	0.000	....
Taxes	....	....	0.237	0.027	....	....	0.022	....	0.006	0.314
Employers' liability insurance	....	....	0.015	0.042	....	....	....		....	....
Production Cost	2.177	0.680	1.888	3.055	2.315	2.394	1.854	1.362	0.524	2.136
Fixed Charges.										
Interest	0.389	0.486	0.881	0.763	0.515	0.666	0.798	0.297	0.489	....
Sinking funds	0.158	0.426	0.470	....	0.236			0.113	....	....
Depreciation	....	....	....	0.635	0.337	0.208	0.486	0.115	0.423	....
Net Cost	2.724	1.592	3.239	4.453	3.403	3.268	3.138	1.887	1.436	....
Surplus	0.498	0.020	0.008	0.344	0.435	0.236	0.364	0.247	0.126	....

proportionately from the operating costs and the overhead costs. The Moose Jaw plant was partly under construction in 1914, which accounts for a portion of its high production costs.

The deductions in the cost of Regina in Table IV represent the value of extra stock on hand in the store rooms at the end of the year. Hence in order to obtain the values in Table V, this was deducted proportionately from the costs of oil waste, etc., from repairs and maintenance of plant and from repairs and maintenance of the distribution system.

Regina was not using its new power plant during all of 1914. Its economical operation ought to make material changes in the power costs of the year 1915.

At Edmonton the Power Plant department has control of the generation of electricity and the pumping of water. It delivers the electricity at its main switchboards or at the direct-current switchboards of its substations either to the street railway or to the electric light and power department which is a separate organization. The report of the superintendent of the power plant showed the operating costs of the steam, gas, water and filtration departments but did not distribute the overhead charges between these subdivisions.

In Table IV the interdepartmental charges were first distributed proportionately among the different items in the summary. Then the overhead charges were distributed on the basis of the total operating costs of the electrical and water plants. This allotted 75 per cent of the overhead charges to the electrical plant and 25 per cent to the water pumping and filtration plants. The latter charge amounted to $10,082.99.

A further analysis of the statements showed a deficit in the water pumping and filtration departments between total revenue and operating costs of $1,119.98. Both this charge and the preceding one of $10,082.99 had evidently been made up out of the revenue of the electrical departments and in Table IV are therefore included in its surplus since the water department operated at a loss.

In addition, the city council in By-law No. 526 set aside the sum of $12,481.26 out of the surplus of the power plant. For the purpose of this analysis this sum is still treated as surplus for the electrical department.

Finally, the statement of the power plant department showed a net surplus over all charges, including the reserve just discussed, as shown by its profit and loss account for 1914, to the amount of $828.33. This also was evidently earned entirely by the electrical department. The true net surplus for the year was therefore $24,512.92.

The electric light and power department of Edmonton has charge of the distribution and sale of its electricity to private consumers. It is an entirely distinct and separate organization from the power plant department and keeps its own sets of accounts. However in these accounts the selling price of the power plant department for electricity is the cost price to the electric light and power department. For the purposes of this discussion, it seemed advisable to combine the statements of the two departments and this was done in Tables IV and V. The electric light and power department showed a net surplus for the year of $55,190.95. Hence the total surplus from the electrical utility was $79,762.90.

The miscellaneous charge for the city of Calgary includes an item for $150,821.63 which was the cost of 26,463.032 kw-hr. purchased from the hydroelectric plants of the Calgary Power Company. This represents an average cost of 0.57 cents per kw-hr. at the city's terminals. Although the city's municipal plant generated the balance of the power used, *i. e.*, 4,928.564 kw-hr., it did not seem fair to make a distribution of costs in Table V on this basis for most of the costs in this plant included "stand-by" charges for keeping the boilers warm and under steam and for having a sufficient labor force on hand in case of emergency demands for power.

The fiscal year for Winnipeg ends April 30th. The figures shown in Table IV and V are for the year ending April 30, 1915, and therefore cover a longer war period than those for the other cities. There may be some difference of opinion regarding the classification of these accounts in Table IV. The figures for wages include the following:

Labor, Hydraulic Plant	$15,392.21
Inspection and Patrolling, Transmission System	6,414.68
Terminal and Substations, Operating Labor	19,523.43
	$41,330.32

The repairs and maintenance costs cover charges similarly distributed. Office expense cost consists of commercial expense of promotion and collection, general office expense, printing and stationery, and war tax. The miscellaneous costs consist of the following:

Tramway to plant, operation and maintenance	$33,795.34
Extraordinary contingencies	18,076.45
Uncollectable accounts	12,000.00
Expenses on consumers' premises and municipal lamps	8,671.80
Undistributed expense	36,988.59
	$109,052.18

Although no fund is set aside for employee's liability insurance, $9,484.60 was paid out in undistributed expense during the year for injuries and damages.

The item " kw-hr. generated " in Tables IV and V for Winnipeg represents the kw-hr. delivered at the terminal substations. It was thought best to use this figure so that the values would be comparable with those of the other cities. The utility's records show the following:

Total kw.-hours generated	70,743,274
" " " delivered at substations	62,493,162
Line and transformation losses	8,250,112
" " " " per cent	11.6

The financial year 1914 was chosen for this analysis of the costs of these plants not only because these reports were the most recent available but also on account of the lack of abnormal conditions of growth during that period. Previous to this year the increases in electrical demands were exceedingly difficult to forecast. A curve showing the growth of electrical demand that is typical of all these Western cities is that for Moose Jaw shown in Fig. 1.

The year 1914 was a poor one financially for these municipal plants. Industrial plants were closed down at the outbreak of war and the utility's power load was thus decreased. This in many cases made retrenchment necessary and all power plant improvements and extensions were suspended. A decrease in load instead of the expected increase, left all plants with excess power capacity. Consequently higher fixed costs and operating costs were the result.

Table V shows very plainly the effects of cheap gas, coal and water power on the cost of electricity in the cases respectively of Medicine Hat, Lethbridge, Calgary and Winnipeg. The two former cities have comparatively small plants which at present are much underloaded and with low load factors. The effect of the high cost of coal is seen very plainly in the costs of the Moose Jaw, Regina and Saskatoon plants. Such utilities should therefore have the most economical plants and methods available. In fact this consideration has not been neglected, for these plants are all provided with steam turbines, economizers, superheaters, CO_2 recorders and other apparatus to improve operating conditions and to reduce plant costs.

It is scarcely fair to compare the fuel costs of these Western Canadian cities with that of Massachusetts as given in Table V, for in the West lower grades of coal with less heating value and higher ash and moisture contents are generally used. Labor also costs more in the West than in Massachusetts.

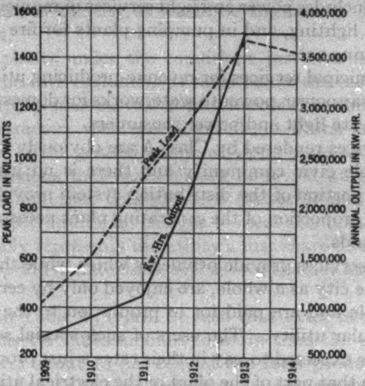

FIG. 1—TOTAL ANNUAL OUTPUT AND PEAK LOAD 1909 TO 1914—MUNICIPAL ELECTRICAL DEPARTMENT, MOOSE JAW, SASK.

TAXATION OF MUNICIPAL UTILITIES

The electrical utilities are taxed as shown in Table IV, in the cities of Lethbridge, Moose Jaw, Edmonton, Calgary and Winnipeg. Only in the case of Lethbridge has the utility been taxed near its full value. In this city, it is held that the utility enjoys the use of the city's streets and alleys for its distribution system and that its business increases with the general improvement of the town. It also receives fire protection and police protection provided by the general taxation of the city. The users of electric light and power thus enjoy privileges at the general expense of the public and should therefore pay in their rates a proportional tax to cover such extra privileges. In the other cities the taxes are only for a portion of the plant or system. The taxes at Winnipeg probably cover property not within the city limits.

The Lethbridge system is based on the right ideas and is more nearly the correct one. In order to determine the most equitable basis for taxation of such municipal utilities it is necessary to study the classes of service they furnish and the privileges these enjoy.

An analysis of the account of the utilities will show that these may be divided into three general classes.

(A) Municipal services other than revenue-producing utilities. This class includes power and light services in municipal buildings, etc.; street lighting, and in pumping plants for fire purposes and street cleaning use.

(B) Municipal services for revenue-producing utilities such as, street railway power, power to waterworks for domestic supply etc.

(C) Private light and power consumers.

The services rendered by Class A are obviously for the benefit of the whole civic community and there is no justification for taxing the portion of the distribution system providing such service or the proportion of the generating plant necessary to supply such demands.

Class B services provide privileges which while they may be of value to the city as a whole, are enjoyed only by certain portions of its people and are paid for in proportion to the use made of this particular utility. The users of such special service should therefore be expected to pay in their rates a just proportion of the taxation on that part of the plant of the electrical utility provided to serve their needs.

It is obvious that customers in Class C enjoy special privileges in the use of the utility's light and power, and should pay for this privilege as a tax on the proportionate part of the system supplying their demands.

It is thus possible to fairly apportion the taxable and tax-free values of the electrical plant and the land occupied and used by the utility. Such apportionment for taxation purposes should be one of the duties of the Provincial Public Utility Commission.

A question naturally arises regarding the special privileges that made the utility subject to taxation. A survey of the following brief summary of certain features of these plants should indicate clearly that there is ample justification for subjecting them to taxation.

In the first place the utility occupies land with a plant, of which a portion is used for other than pure civic purposes and produces revenue. It is therefore subject to taxation under all usual plans of assessment and particularly so in those Canadian cities under single-tax. The utility uses the city's streets and alleys for poles and conduits and enjoys fire and police protection as already mentioned. The city's credit was employed in marketing the debentures to build the plant and its credit is still used in purchasing fuel, labor and supplies. Considerable time of the city's executives is devoted to consideration of the utility's special problems and thus a portion of the cost of municipal government is rightly chargeable to the utility. The utility furthermore pays no franchise tax to the city as would be the case in a privately owned system.

Municipal plants under the conditions just enumerated are able to serve private customers at rates below the cost at which they could supply such service themselves and in this way provide these consumers with special privileges which are enjoyed at the expense of the general public when no taxes are paid. It is therefore obvious that taxes should be levied on portions of these utilities and that consumers of classes B and C should pay in their rates, additional charges to meet this taxation which in the end really represents the utility's just share of the general administrative and maintenance expenses of the city as previously outlined.

Referring to Table V, it will be seen that taxes in the case of the Massachusetts cities amount to more than the plant labor costs and form about 15 per cent of the total production cost.

Funds are set aside for employers liability insurance in the case of two cities. Workmen's compensation acts are in force in these provinces. Some of the cities include compensation charges in their miscellaneous expenses, but do not carry insurance for the same.

DEBENTURES ISSUES AND SINKING FUNDS

Yearly charges for sinking funds have been figured out in most cities and are paid out of revenue, though in Moose Jaw only a depreciation fund is maintained.

In Winnipeg, standard rates of depreciation are applied to the different parts of the plant. The average rate for the whole system approximating 4 per cent. of the total investment. It was considered unjust to the Winnipeg tax-payers and current-users of the present generation and unduly beneficial to future generations that both sinking fund and depreciation reserve should be provided. The Public Utility Commissioner of Manitoba ordered that whatever sums are necessary for payment to the sinking funds shall be taken from the depreciation reserve. This sinking fund withdrawal amounts to about 1.8 per cent on the total investment. The balance of about 2.2 per cent is carried as a depreciation reserve for plant replacement. The statements of the municipal department show only a change to depreciation, from which later a transfer is made to the Sinking Fund Trustees appointed by the Judiciary. Hence the depreciation charges in Tables IV and V should really be divided into two portions, one amounting to about eighteen-fortieths being allotted to sinking funds and the balance forming the true depreciation reserve. This method of financing is perfectly sound though it differs somewhat from usual practise.

The investment and use of these sinking funds presents a problem that has received much attention in the West. Some of these funds have been invested in other municipal securities, and in school debentures. Loans have been made on mortgages, while in a few places the money simply draws interest in the banks. In times of depression it would be hard to realize on some of these investments in case this were necessary. There is also the temptation in bad years to fail to set aside the full amount, hoping to make up the deficit at a later date. During depressions it is sometimes impossible to collect all the taxes and in such cases the sinking funds often do not receive their full allotment.

There is necessarily a large element of risk in investments earning high returns and such use of sinking funds should be closely scrutinized. As these funds are public monies, they should only be used in absolutely safe investments.

An innovation in municipal finance has been brought before the public in order to remove these elements of risk incurred with sinking funds. This consists of the substitution of serial debentures for the ordinary long-term debenture with its sinking funds. In the end the cost to the public is the same provided the two bonds can be sold at the same price. In the case of the serial debentures an installment of the principal is paid off each year together with the interest charges on all outstanding bonds for that year. This relieves the municipal councils of the responsibility for sinking fund investment and lifts a considerable burden from their shoulders.

A statement of the case for serial bonds is put very concisely in the following paragraphs from Document 23 of the State of New York's Constitutional Convention.

> The most certain, simple and cheap way to amortize a debt is to pay it off in annual installments. The uncertainties of calculation which have so unfortunately affected our sinking funds in the past are at once eliminated. There is no large fund left in the hands of public officials to be cared for and invested and reinvested for fifty years with all the attendant risk and temptation, and the danger that this power of investment in various local securities may be perverted into a political power is entirely removed. Furthermore, the fact that the same administration that incurs a debt must at once begin within a year to make provisions for its retirement, necessarily and strongly tends towards responsibility and prudence in the contraction of the debt.

It has been maintained that investors prefer long-term securities and in consequence the serial debentures could not be marketed at as favorable prices as under present methods. Several prominent Canadian bankers who were consulted regarding serial bonds, expressed the opinion that there would now be practically no difference in placing the serials at as favorable rates as the long-terms.

One leading American banker pointed out that, at the time of writing, short term bonds commanded better prices than long term securities and that he believed serial bonds could sell fully as well if not better than sinking fund securities.

Document 23 of the New York Constitutional Convention may be quoted with interest on this subject. Referring to the marketability of serial bonds, it is stated:

> After careful investigation, however, your committee is of the opinion that serial bonds are quite as marketable as sinking fund bonds. At a recent sale by the Finance Department of New York City, where a sale of serial bonds was made side by side with sinking fund bonds, the former brought when reduced to terms of equivalent maturity, a better price than the latter, the Comptroller of the city attributing the success to the serial bonds. Inquiry among the large financial houses of New York, Boston, Chicago and Philadelphia has developed practically the unanimous opinion of those authorities that serial bonds are at least as marketable as sinking fund bonds. The system has already been adopted by other States of the Union and is also now in use by many of the cities and smaller subdivisions of this State.

There is a strong temptation in the West to adhere to the sinking fund plan, for often the municipalities are able to invest these funds at rates higher than the interest charges on the debentures and thus they relieve their municipalities of a certain amount of taxation. In spite of the element of risk this is often considered very clever administration.

One further objection to the long term bonds, deserves mention here. Such a bond requires only a comparatively small annual sinking fund charge, which is attractive to an uninformed tax-payer. On the other hand, if an adequate depreciation fund is not set aside to provide replacement of plant at the proper time, owing to the low sinking fund charges, low rates may be quoted at the expense of future consumers. For after the plant has had to be renewed such consumers will not only continue to pay interest and sinking fund charges on the old plant which was worn out by their predecessors and hence is of no benefit to them, but will also have to pay similar charges on debentures that have to be issued to renew the plant. This is unfair discrimination against future consumers.

Attention has already been called to the long life of many of the debentures. It is certain that the plants which these debentures cover, generally cannot last their full terms. At a certain time they will be worn out and have only scrap value or they may become obsolete, yet the original debentures will still be unredeemed. The more equitable and just system is the modern method of limiting the term of the bonds to the life of the improvement they are to cover. This practise is required by law now in several of the American states.

There seems to be a tendency among accountants and some engineers to over-estimate the life of electrical machinery as used to-day. If one considers for a moment, merely the changes brought about in the last fifteen years by the steam turbine in the power plant and by new lamps and fixtures in the art of illumination, and then if one further determines the number of machines bought so long ago that are still economically serviceable in growing cities, it will become apparent that the estimates of the life of the plant made fifteen years ago have been entirely misleading and in error due to obsolescence either from improvement in the art or from inadequacy in capacity. Apparently such progress is not at an end and present-day machinery will be subject to the same influences. It would be well then for municipal authorities to give careful attention to this phase of the situation when deciding on the probable life of their plant and the debentures to cover the same.

The adoption of serial bonds and the adjustment of their maximum term to the life of the improvement they are intended to cover, will provide an equitable and just method of financing future developments. The question naturally arises whether it would be wise or necessary to readjust the present outstanding securities. It has been suggested that these be exchanged for serial bonds properly adjusted to the life of the improvements they cover. But such could only be accomplished with the consent of the outstanding bondholders. It is probable that this would involve some difficulty on account of the holdings being largely in Europe where any financial innovations would be looked upon with suspicion.

DEPRECIATION AND OBSOLESCENCE

Probably the most frequent criticism one hears of municipal ownership is that adequate depreciation funds are not set aside. When renewals become necessary, these must be made either at the expense of the taxpayer instead of the consumer who enjoys the utility, or more debentures must be issued. The larger cities of Western Canada are apparently providing suitable depreciation funds which represent the difference between the life of the plant and that of their debentures, so that the combined funds will replace the plant at the end of its usefulness. Investigation tended to show that the credit for this foresight was largely due to the work of competent auditors rather than to the initiative of the municipal councils.

The smaller cities do not seem to maintain this fund and for that reason their surplus has been declared at the expense of future replacement funds. A study of the situation in each of these cities would undoubtedly lead to the establishment of a depreciation fund even at the expense of slightly increased rates.

The question of obsolete machinery presents many difficulties. Most of the cities have outgrown their first electric plants and these have either been scrapped or are virtually obsolete as reserves. In many cases some of the machines now in use will soon be too small and uneconomical if the city continues to grow. Yet practically the whole value of these former plants is covered by debentures on which the present consumers are paying interest and sinking fund charges. The question arises as to how this obsolescence charge shall be financed.

At Edmonton, the capital account for obsolete machinery in the various plants is excessive, as is evident from the high plant values in Tables IV and V. The former Superintendent, R. H. Parsons, made a commendable effort to wipe out as much of this as possible. In 1912 the power plant was granted $100,000 out of general taxation funds for this purpose. The sum of $170,000 was set aside in 1913 from the power plant revenues for depreciation and obsolescence and in 1914 a sum of $87,817.00 was again set aside for a similar purpose. It was hoped that this obsolescence charge would be totally wiped out in 1915.

War conditions, however, made reductions in rates advisable and considerable still remains to be written off the accounts.

In 1913 the auditors recommended a general tax to meet this charge on the basis that the city would be paying for "errors of past years," but this suggestion was not adopted. When this charge for obsolete machinery has been removed either by the retirement of debentures or the replacing of inefficient equipment by modern machinery out of the special depreciation and obsolescence funds, it is estimated that the utility can reduce its charges by about 40 per cent.

An appraisal of the plant at Moose Jaw in 1914 showed a sum of $37,700 unaccounted for out of the debenture issue. It will be necessary in the near future to provide a fund to meet this discrepancy and also to provide for some of the fire losses not covered by insurance.

It therefore seems necessary in certain cases to wipe off at once the charges for obsolete machinery either by general taxation or by funds from current revenue secured by increased rates. The latter plan appears to be the more equitable and just of the two, for those enjoying the utility are then paying all its costs.

CHARGES FOR MUNICIPAL LIGHTING AND STREET RAILWAY POWER

The revenues of the electric power utilities are dependent to some extent on the rates charged the city for street lighting and the street railway for power. These rates will now be discussed.

Medicine Hat has no electric street lighting or street railway.

The Lethbridge electrical utility charges the street railway department two cents per kilowatt-hour for power. The city lighting equipment belongs to the electrical utility. The city is charged with all repairs and maintenance on this system and pays for power at the net plant cost, including fixed charges on the lighting systems.

Moose Jaw has a street railway owned by a private corporation and operated by Diesel engines. The municipal power plant charges the city the actual cost of maintenance of its lighting system plus a meter rate of two cents per kw-hr. for arc lamps and 2½ cents per kw-hr. for incandescent lamps.

In Saskatoon the street railway is charged 1½ cents per kw-hr. for the direct current it takes from the switchboard of the electrical plant. The city is charged at the rate of $70.00 per year for its arc lamps while tungsten lamps for street lighting and municipal buildings are charged at the regular rates, viz.: eight cents for the first 100 kw-hr., seven cents for the next 50 kw-hr. and six cents for all over 150 kw-hr. per month.

At Regina, the city is charged by the utility, 2¼ cents per kw-hr. plus a service charge of 50 cents per connected kilowatt per month on 428 kw. for street lighting. This does not include repair and maintenance charges. The street railway pays 1¾ cents per kw-hr. for the power used plus a service charge of 50 cents per month per connected kilowatt on 1000 kw. The power is measured on the direct-current terminals leaving the switchboard.

The street railway paid 2 cents per kw-hr. for its power at Edmonton in 1914. For general street lighting the rate is 3.1 cents per kw-hr. plus maintenance and operation cost plus 3½ per cent for departmental charges. The city of Edmonton also pays 5 per cent on capital expenditure for the street lighting system. The city has built a "Whiteway" on Jasper Avenue which is handled differently from the other lighting charges. In this case the charge is 3.1 cents per kw-hr. plus maintenance and operation costs plus 3½ per cent for departmental charges. Two thirds of this gross sum is charged to local improvements as a frontage tax and one third to the city of Edmonton. The city also pays 5 per cent interest on its third of the capital expenditure. The balance of the capital expenditure was charged up to local improvements when the system was built.

Vol. 35
1916

Street lighting in Calgary costs a fixed sum per lamp per year. This varies from $65.00 for a magnetite arc lamp to $6.00 for a 16-c. p. incandescent lamp. The street railway pays 1.5 cents per kw-hr. for its power measured on the direct-current wattmeters on the outgoing feeders from the substations.

The street railway at Winnipeg is operated by a private corporation with its own power supply. The city is charged 0.875 cent net per kw-hr. for street lighting and 0.625 cent net per kw-hr. for water pumping, for electrical service from the municipal plant.

There is evidently no uniformity of practise in charging for street lighting and for power used by other utilities. Street lighting usually produces a higher load factor than similar service to private consumers. Water pumping also provides a high load factor and is very desirable service when pumping can be done in off-peak hours. Street railway service on the other hand frequently has no better load factor than other commercial power.

It would therefore seem best to charge for all these services in two parts; first, a demand charge covering the fixed charges of that portion of the plant needed to meet maximum demands, giving proper consideration to when these occur, and second, a meter rate on all current furnished, which rate would consist of operating and distribution costs together with a certain proportional part of the overhead and management charges.

THE DISPOSAL OF SURPLUS

In regard to the disposal of surplus, at Kamloops this was carried to a summary account where it balanced the losses incurred in the operation of other utilities.

The profits were small in the case of Medicine Hat and of Lethbridge and were carried over into current revenue. The surplus of Regina and of Saskatoon are carried over into general revenue accounts where they offset in a measure the deficits incurred in the operation of the municipal street railways.

At Moose Jaw the surplus is transferred to the account for municipal street lighting where it balances two-thirds of the cost of this service. This practise is wrong, for street lighting is a public convenience and necessity to the whole community and should therefore be at the expense of the city as a whole. The costs of such service should be included in the general taxes just the same as the cost of sewage disposal, fire and police protection.

Calgary had a total surplus reserve of $154,850.91 set aside by the end of 1914. No purpose has been allotted to the reserve up to the present time. Rates were reduced in 1915 and in consequence it is probable that the surplus for that year will be small.

Edmonton's surplus as already explained consists of the following items:

Power plant's net surplus	$ 828.33
Reserve set aside by By-Law No. 576	12,481.62
Waterworks charges taken out of electric revenue	11,202.97
Surplus in distribution dept	55,190.95
Net Surplus	$79,703.87

Of this amount the waterworks charges should be assumed by the water department by increased rates. The distribution department has now a total surplus reserve of $104,682.47. This has been distributed as follows:

Deficit of Strathcona	$6,554.49
Obsolescence Reserve	15,000.00
Reserve for Underground Construction	83,127.98

It seems hard to justify the use of this surplus for underground construction when the funds are taken from current revenue. This is a case where permanent improvements are being made out of the receipts from current lighting and power rates.

At the beginning of the fiscal year Winnipeg had a deficit of $81,409.89 remaining from a total deficit of $142,273.64 incurred during the first two years of operation. The surplus for the current year was applied to this account reducing the net deficit on April 30th, 1915, to $2,725.17, which will probably be wiped out this year and permit lower rates to be quoted to customers.

The variations in practise as set forth in the preceding paragraphs raises the question as to the proper disposal of surplus. The municipalities argue that the utilities are theirs, that they have earned profits which belong therefore to the community, and the city through its governing board can dispose of this surplus as it deems proper.

However, if the situation is analyzed carefully certain facts will be revealed which raise questions as to the equity of the above practise. In the first place these profits accrue out of rates paid by the consumers of light and power and they are therefore paying in their rates more than it is costing the city to provide such service. Suppose such profits are used, as is frequently the case, to make good a deficit in another department, say in the water department, then the consumers of water are paying rates that are lower than the city's gross cost for supplying water. One is then confronted with this situation ,that the electric light users pay a portion of the cost of the water consumer's service. The injustice of this condition is at once apparent. The same reasoning applies in regard to balancing street railway deficits by surplus funds.

On the other hand if the surplus is carried to a general revenue account, and is used to defray the current expenditures of the city or to meet specific civic costs, such as street lighting, it virtually takes the place of additional taxes. Then the electrical consumers are paying a portion of the city's general taxes in addition to the cost of supplying them with power and light. This is neither fair nor just if the utility has already paid taxes on its valuation. If it has not been taxed, then there is a considerable measure of justification for this practise.

Reference has already been made to the practise at Edmonton of utilizing the surplus for permanent improvements. In general when such funds are used either to replace old equipment, to extend the utility or to make permanent improvements in the system, the benefits of such will be enjoyed by future consumers extending over a period of years. They alone should bear the costs of such improvements and it is therefore unjust to levy high rates on present consumers that provide funds for improvements they do not enjoy when paying those rates.

In cities where a proper depreciation and obsolescence fund has not been provided, it would seem necessary to set aside at once all surplus funds in a special sinking fund to make up for failures in the past to provide for this cost.

How then should the surplus be used? In every power plant there are at times emergencies that call for expenditures in excess of the current costs of other periods, such for instance as damages to the system from sleet storms, lightning, floods and fires. It would seem reasonable therefore that a special reserve fund of moderate amount should be set aside for this purpose out of the profits earned.

The use of surplus to provide for deficient depreciation funds has been pointed out. This procedure is so reasonable and rational that no argument need be presented to justify it, for sooner or later such funds must be forthcoming and rightly should be provided by the users of the utility.

When profits exceed reasonable allowances for the two preceding purposes, then the consumers are entitled either to a proportional rebate on their bills or to reduced rates for the following year. The former method has certain psychological advantages as it emphasizes the cooperative features of the enterprise and the mutual profit and loss characteristics of municipal undertakings, and also obviates the political pressure brought to bear on officials when rate changes are to be made.

If rates were reduced in proportion to surplus, the reductions would amount to from 7 to 15 per cent in the different cities, with the exception of Medicine Hat and Lethbridge.

Table VI contains some interesting deductions from Table V. Winnipeg figures are for the municipal plant only and do not include the large private corporation operating the street railway and also selling light and power in the city.

The plant equipment per 1000 inhabitants averages nearly twice that of the average of nineteen cities in Massachusetts. The electrical consumption per inhabitant is more than twice the eastern average.

The average of kw-hr. generated per kilowatt capacity of plant for the Canadian cities amounts to 1457 kw-hr. This indicates that practically the same station load per kilowatt installed exists in the West as in the Massachusetts cities. The equivalent coal per kw-hr. was figured from the cost of coal per ton of 2000 pounds and the fuel cost per kw-hr. as given in Table

TABLE VI.—GENERAL DATA ON PLANT OPERATION.

City	Plant capacity per 1000 inhabitants kw.	Debenture issue per inhabitant	Kw-hours generated per year per inhabitant	Kw-hours generated per year per kw. of plant capacity	Pounds of coal per kw-hour	Operating cost less fuel per kw-hour	Distribution cost per kw-hour	Overhead costs less taxes per kw-hour	Production cost less fuel and taxes per kw-hour	Fixed charges per kw-hour	Net Cost less fuel and taxes per kw-hour
Kamloops	491	$96.45	478	973	5.48	0.576	0.069	0.190	0.835	0.547	1.382
Medicine Hat	333	47.77	339	1016	....	0.417	0.109	0.117	0.647	0.912	1.559
Lethbridge	230	68.96	341	1484	6.25	0.753	0.254	0.275	1.282	1.351	2.633
Moose Jaw	150	35.39	187	1247	7.64	0.712	0.572	0.351	1.730	1.398	3.128
Saskatoon	238	41.91	388	1491	4.11	0.530	0.199	0.219	0.948	1.088	2.036
Regina	190	37.16	233	1226	5.23	0.582	0.272	0.181	0.982	0.874	1.856
Edmonton	205	56.60	438	2139	4.68	0.658	0.158	0.228	1.078	1.284	2.362
Calgary A	142	25.36	392	....	....	....	....	....	1.179	0.525	1.704
Calgary B	167	....	478	....	....	....	....	....	....	....	....
Winnipeg	150	35.92	312	2083	....	0.127	0.073	0.143	0.508	0.912	1.420
Average of 19 cities in Massachusetts	113	....	165	1462	3.12	0.338	0.423	0.344	1.252	....	....

" Calgary A " refers to the municipal plant only.

" Calgary B " includes the private corporation which has a franchise in the city. It has a plant of 2000-kw. capacity and delivers about 2,000,000 kw-hr. per year.

V. The Lethbridge plant consumes the whole output of its mine without much hand picking of the coal. The coal is rather low grade and high in ash. Hence the fuel consumption is apparently excessive.

The high coal consumption of Moose Jaw together with other high production costs is due in a large measure to the fact that half the boiler room was under construction during the financial year 1914.

Considerable high grade Pennsylvania coal was burned during the year at Saskatoon which partially accounts for the low coal consumption. A survey of these figures on coal indicates that power costs can be considerably reduced by improved plant operation. The cost of fuel per kilowatt varies widely as shown in Table V. This item in the total cost was therefore eliminated from the figures given in Table VI in order that a more equitable basis of comparison might be obtained.

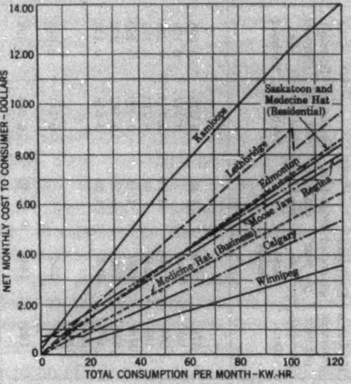

Fig. 2—Monthly Lighting Charges to Small Consumers

The column of " operating costs less fuel charges " indicates very clearly the influence of the high labor costs due to higher wages in the west as compared with those of the Massachusetts cities. Cheaper service may be expected then by reducing labor costs per unit of output as well as cutting down fuel costs.

Western distribution costs with the exception of Moose Jaw are generally low, possibly because the systems are comparatively new and have not needed extensive repairs. The item of taxes was also omitted from the costs presented in Table VI as there was no uniformity of practise in regard to this charge. The office and management costs of these western utilities are low compared to the Massachusetts costs.

The average production cost less fuel and taxes is 1.021 cents per kw-hr. for the western cities against 1.252 cents per kw-hr. in the Massachusetts cities. The average fixed charges of the Canadian cities are 0.988 cent per kw-hr. or nearly the same as the production cost without fuel or taxes. The average net cost without fuel or taxes amounts to 2.009 cents per kw-hr. From Table V the average net cost including fuel and taxes is 2.793 cents per kw-hr.

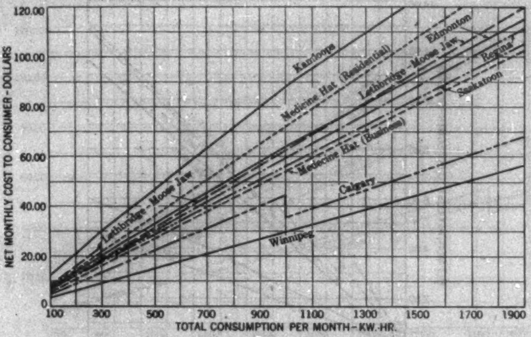

FIG. 3—MONTHLY LIGHTING COSTS TO LARGE CONSUMERS

RATES FOR LIGHT AND POWER SERVICE

The rates for lighting and power with the prompt payment discounts in the various cities are given in Tables VII and VIII, and are shown graphically in Figs. 2, 3, 4 and 5. These curves are plotted with total kilowatt-hours consumption per month per consumer as one ordinate while the other indicates the net monthly cost to the consumer when he avails himself of the prompt payment discounts. Comparison can be made between the different cities by selecting any given consumption and noting from the curves the net cost in each city. Rates of other cities can be compared by figuring the net cost of a given electrical consumption and comparing it with the charges in the Western plants as shown by the curves.

The curves showing the lighting rates for Regina for large consumers are not absolutely correct for they do not include the service charge of 50 cents per kilowatt of connected load. As no data are at hand in this case regarding the relation of connected load to consumption, it was impossible to plot curves representing true conditions. The actual cost can be found by adding the service charge to the figures given by the curves. The curve for charges to small consumers has been plotted on the assumption of one kw. connected load per customer, and may thus be slightly in error for any particular case. No attempt was made to show the two meter rates of Moose Jaw and other places.

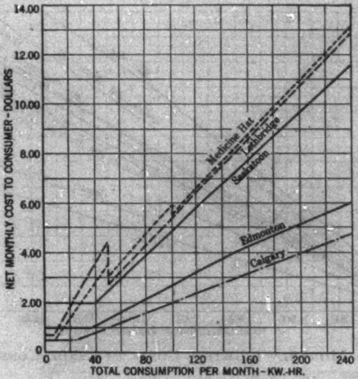

FIG. 4—MONTHLY POWER COSTS TO SMALL CONSUMERS

The effect of the general use of natural gas for domestic lighting and of the effort to build up a large power load is shown in the high domestic lighting rates at Medicine Hat.

A service charge of 50 cents per month per kilowatt of demand is charged at Regina against the customer. It is maintained that this covers the so-called "customer charge" consisting of the costs of reading meters, billing, etc., and also a portion of the demand charge on the plant which consists of the charges on capital to maintain capacity in the station ready to serve customers. Flat rates are also still in existence in some cities.

Medicine Hat, Lethbridge and Calgary charge for light and power on a "sliding scale" basis, as shown in Figs. 3 and 5. In order to show the unfairness of rates charged on this basis take for example the Medicine Hat rates to two consumers using respectively 645 and 655 kw-hr. per month. The charges, are as follows:

1st consumer 645 kw-hr. .. 4½ = $29.02
2nd " 655 " · 4 = 26.20

The second consumer uses 10 kw-hr. more than the first consumer yet actually pays $2.82 less for his total power. No analysis of costs could possibly justify such a practise, for the smaller consumer is manifestly discriminated against.

It has been pointed out that the large consumer is entitled to some consideration in rates but these should be adjusted to the cost of service. Hence if an analysis of costs justifies the Medicine Hat rate of say 4½ cents per kw-hr. for the first 650 kw-hr. per month, then the consumer should pay that amount regardless of his total consumption. If, however, additional power over 650 kw-hr. can be provided to one customer at a lower cost than 4½ cents per kw-hr. then the consumer is entitled to a correspondingly lower rate for his consumption over and above the first 650 kw-hr. only.

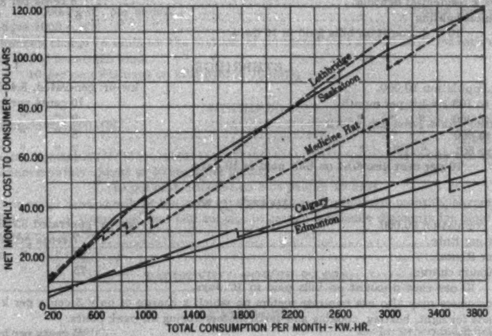

FIG. 5—MONTHLY POWER COSTS TO LARGE CONSUMERS

General cost curves could not be plotted from the power rates given in Table VIII for the cities of Kamloops, Regina, Moose Jaw and Winnipeg.

TABLE VII.—RATES FOR LIGHTING.

KAMLOOPS.

Population 5500. kw-hr. generated 2,628,100

Flat Rate	10 c. p.	16 c. p.
Each light per month (not to exceed two lights)	1.25	2.00

Discount if paid within 10 days—20%.

Meter Rate.

First 50 kw-hr.	14 cents per kw-hr.
Next 50 "	12 " " "
Next 200 "	10 " " "
Next 700 "	9 " " "
Over 1000 "	8 " " "

1 cent per kw-hr. discount will be allowed if paid within 10 days from date due.

Meter rent 25 cents per month.

MEDICINE HAT

Population 9000. kw-hr. generated 3,050,070.

Private residential lighting	8 cents per kw-hr.
Business lighting	6 " " "

10% discount on bills paid in 10 days.

LETHBRIDGE

Population 10,000. kw-hr. generated, 3,415,000.

Up to 100 kw-hr. per month	10 cents per kw-hr.
101 to 300 " " "	9 " " "
301 to 600 " " "	8 " " "
Above 601 " " "	7 " " "

10 per cent discount on bills paid in 10 days.

MOOSE JAW

Population 20,000. kw-hr. generated 3,739,990.

Lighting Rate	7 cents per kw-hr.
Meter Rental	25 " " month
Minimum charge	75 " " "

10 per cent discount on bills paid in 10 days.

Customers may also use two-rate meters on which a charge of only 3 cents per kw-hr. is made for light, heating, cooking and small motors during off-peak hours.

Meter Rental	25 cents per month
Minimum charge	3.00 per month.

10 per cent discount on bills up to $40, paid in 10 days.

15 per cent discount on bills over $40, paid in 10 days.

SASKATOON.

Population 25,000. kw-hr. generated 8,873,642.

First 100 kw-hr. per month	8 cents per kw-hr.
Next 50 " " " "	7 " " "
All over 150 " " "	6 " " "

Minimum monthly charge $1.00.

10 per cent discount on bills paid in 10 days.

REGINA.

Population 40,000. kw-hr. generated 9,315,355.

First 300 kw-hr. per month	7 cents per kw-hr.
All over 300 " " "	6 " " "

Service charge 50 cents per kw. of demand.

Burned out lamps renewed by city free of charge.

10 per cent discount on bills paid in 10 days.

Special discounts for large lighting consumption.

Vol. 35
1916

EDMONTON

Population 50,000. kw-hr. generated 21,927,089.

1 to 100 kw-hr. per month	7½ cents per kw-hr
101 to 400 " " "	7 " " "
401 to 1000 " " "	6½ " " "
1001 to 2200 " " "	6 " " "
All over 2201 " " "	5½ " " "

Minimum monthly charge 75 cents.

No discounts allowed on accounts less than $1.00.

5 per cent discount on bills paid in 10 days.

The following schedule cover the charges for sign lighting:

1 to 375 kw-hr. per month	5 cents per kw-hr.
376 to 5000 " " "	3 " " "
All over 5001 " " "	2 " " "

A schedule of minimum charges per kw. of connected load for each month of the year has also been prepared but is not quoted in this paper.

10 per cent discount allowed on bills paid in 10 days.

CALGARY.

Population 80,000. kw-hr. generated 31,391,596.

First 1000 kw-hr. per month	5 cents per kw-hr.
All above 1000 " " "	4 " " "

Minimum charge 75 cents for the first kw. of connected load and 50 cents for each additional kw. of connected load.

10 per cent discount on bills paid in 10 days.

WINNIPEG.

Population 200,000. kw-hr. delivered at city terminal 62,493,162.

Domestic lighting	3⅓ cents per kw-hr.

Minimum monthly charge of 50 cents per meter.

10 per cent discount on bills paid in 10 days.

Commercial lighting sells at the same rate but with a net minimum monthly payment of $1.00 per kw. of connected load and subject to certain wholesale discounts for large consumption not quoted.

TABLE VIII.—POWER RATES.

KAMLOOPS.

Population 5,500. kw-hr. generated 2,628,100.

Five classes of power rates are in effect, A for small motors; B for medium sized motors; C for large motors; D for irrigation pumping and E for heating and cooking off-peak.

Class A Power.
$6 per h. p. per year plus

First 50 kw-hr.	6 cents per kw-hr.
Next 100 "	4 " " "
All over 150 and under 500 kw-hr.	3 " " "

Class B Power.
$6 per h. p. per year plus

First 500 kw-hr.	3½ cents per kw-hr.
Next 1000 "	2 " " "
Over 1500 and under 2500 kw-hr.	2½ " " "

Class C Power.
$6 per h. p. per year plus

First 2,500 kw-hr.	3 cents per kw-hr
Next 4,000 "	2½ " " "
Next 5,000 "	2 " " "
Next 10,000 "	1½ " " "
All over 21,500 "	1¼ " " "

Class D. Irrigating only.

First	2500 kw-hr.	2½ cents per kw-hr.
Next	2500 "	2 " " "
All over	5000 "	1½ " " "

Class E. Heating and Cooking.

Off-peak load	3 cents per kw-hr.

Meter rent for all classes, 25 cents per month.

10 per cent discount on bills paid in 10 days.

MEDICINE HAT.

Population 9000. kw-hr. generated 3,050,070.

50 to 100 kw-hr. per month	6 cents per kw-hr.
101 to 250 " " "	5½ " " "
251 to 450 " " "	5 " " "
451 to 650 " " "	4½ " " "
651 to 850 " " "	4 " " "
851 to 1,050 " " "	3½ " " "
1051 to 2,000 " " "	3 " " "
2001 to 3,000 " " "	2½ " " "
3001 to 5,000 " " "	2 " " "
5001 to 25,000 " " "	1½ " " "
Over 25,000 " " "	1 " " "

Minimum charges, $1.00 per month per h. p., single-phase motors.

$.50 per month per h. p. three-phase motors.

The following discounts are allowed on bills for prompt payment.

For the first $100 per month consumption		no discount:
For the second $100 " " "	excess over $100	10 per cent.
For the third $100 " " "	" " $200	20 "
For the fourth $100 " " "	" " $300	30 "
For the fifth $100 " " "	" " $400	40 "
From $500 to $1000 " " "	" " $500	50 "
Excess over $1000 " " "	" "	60 "

LETHBRIDGE.

Population 10,000. kw-hr. generated 3,415,000

There are three schedules in force, the Peak, the Off-Peak and the Flat Rates.

PEAK SCHEDULE.

Up to 50 kw-hr. per month	10 cents per kw-hr.
50 to 250 " " "	6 " " "
251 to 500 " " "	5½ " " "
501 to 1000 " " "	5 " " "
1001 to 3000 " " "	4 " " "
Over 3000 " " "	3½ " " "

OFF-PEAK SCHEDULE.

Up to 100 kw-hr. per month	10 cents per kw-hr.
100 to 500 " " "	5 " " "
501 to 1000 " " "	4 " " "
1001 to 3000 " " "	3 " " "
Over 3000 " " "	2 " " "

10 per cent discount on bills paid in 10 days.

To obtain these off-peak rates the consumer must install a time switch which will be under the control of the city and be adjusted by the city to conform to the following hours.

Between the hours of 1 a.m. and 6 p.m. from February 1st to December 1st.

" " " " 1 a.m. and 4.30 p.m. from December 1st to February 1st.

FLAT RATES.

These are quoted only for large sizes of motors and for use during off-peak hours and are not given here.

MOOSE JAW

Population 20,000. kw-hr. generated 3,739,990.

Horser power of motors or peak load	Fixed charges per h. p. per month or per h.p. of maximum demand	Meter rate per kw-hr. of consumption
1 to 3	$1.00	3.5
4 to 10	1.00	3.0
11 to 25	1.00	2.5
26 to 50	1.00	2.0
50 to 100	1.00	1.5
Over 100	1.00	1.25

Total charge equals fixed charge plus meter charge.

All charges are classified as follows:

Class "A"—24 hours	unrestricted use	100 per cent of base rate.
" "B"—24 "	restricted "	90 " " " "
" "C"—10 "	unrestricted "	90 " " " "
" "D" 10 "	restricted "	66.6 " " " "

The restricted hours are as follows:

October 15th to October 31st	5.30 to 6.30 p. m.
November 1st to November 30th	5.00 to 6.30 p. .m
December 1st to January 15th	4.30 to 6.30 p. m.
January 15th to February 16th	5.00 to 6.30 p. m.
February 16th to March 1st	5.30 to 6.30 p. m.

10 per cent discount on bills paid in 10 days.

SASKATOON.

Population 25,000. kw-hr. generated 8,873,642.

First	750 kw-hr. per month	5.4	cents per kw-hr.
Next	2250 " " "	3.25	" " "
Next	1000 " " "	2.34	" " "
Balance over 4000	" " "	2	" " "
Domestic power		4	" " "
Minimum charge		$2.00 per month.	

10 per cent discount on bills paid in 10 days.

REGINA.

Population 40,000. kw-hr. generated 9,315,355.

First	300 kw-hr. per month	5	cents per kw-hr.
Second	300 " " "	4	" " "
Third	300 " " "	3½	" " "
All in excess of 900 per month		3	" " "

Service charge of 50 cents per month per kw. of demand.

The city uses two-rate meters on which the off-peak rates are as follows:

First	1000 kw-hr. per month	3	cents per kw-hr.
Second	1000 " " "	2½	" " "
All in excess of 2000	" " "	2	" " "

The restricted hours are 6 p. m. to midnight from April 1st to September 30th, from 5 p.m. to midnight during March and October and from 4 p. m. to midnight from November 1st to February 28th.

10 per cent discount on bills paid in 10 days.

EDMONTON.

Population 50,000. kw-hr. generated 21,927,089.

Domestic power not used for commercial purposes costs 4 cents per kw-hr.

Minimum charge 50 cents per kw. of connected load.

GENERAL POWER RATES.

First	150 kw-hr. per month	3	cents per kw-hr.
151 to	300 " " "	2½	" " "
301 to	5000 " " "	1½	" " "
All over	5000 " " "	1	" " "

10 per cent discount on bills paid in 10 days.

The minimum monthly charges are as follows:

(a) Heating or apparatus other than motors, 50 cents per kw. of connected load.
(b) Single-phase notors up to 3 h. p., 50 cents per h. p. of connected load.
(c) Single-phase motors above 3 h. p., 25 cents per month per h. p. of connected load.
(d) Three-phase motors, 25 cents per h. p. of connected load.

In (a) and (b) the minimum monthly charge is $1.00.
In (c) and (d) the minimum monthly charge is $2.25.

Stand-by Service.

A minimum charge of $1.00 per kw. of connected load per month is made for this service No service is supplied for less than 25 kw. of demand.

CALGARY.

Population 80,000. kw-hr. generated 31,391,596.

1 to	750	kw-hr. per month	2 cents per kw-hr.
751 to	1,750	“ “ “	1.8 “ “ “
1751 to	3,500	“ “ “	1.6 “ “ “
3501 to	12,500	“ “ “	1.3 “ “ “
All above	12,500	“ “ “	1.1 “ “ “

A minimum charge of 50 cents per month per h. p. of connected load is made.

When the current is used during off-peak hours only and the amount of current exceeds 130 kw-hr. per connected h. p. per month, the following discounts are allowed:

5 per cent discount for consumptions of 130 to 250 kw-hr. per connected h. p. per month.
10 per cent discount for consumptions of 251 to 300 kw-hr. per connected h.p. per month.
15 per cent discount for consumptions over 300 kw-hr. per connected h. p. per month.

WINNIPEG.

Population 200,000. kw-hr. delivered at city terminals, 62,493,162.

Electric service heating, 1 per cent per kw-hr.

Alternating-Current Power Rates.

The first	50	hours use per month of total connected load	3½c. per kw-hr.
“	50	“ “ “ “ “ “ “ “	2.5c. “ “
“ “	50	“ “ “ “ “ “ “ “	1.9 “ “
“ “	50	“ “ “ “ “ “ “ “	1.4c. “ “
“ “	50	“ “ “ “ “ “ “ “	1.1c. “ “
Excess over	250	“ “ “ “ “ “ “ “	0.8c. “ “

Minimum monthly payment, 75 cents per h. p. of total connected load.

Prompt payment discounts	1	year contracts	10	per cent.
	3	“ “	15	“
	5	“ “	20	“

All the above rates are subject to the following wholesale discounts:

For the first	$100	per month consumption		no discount.
“ “ second	$100	“ “ “	excess over $100	10 per cent.
“ “ third	$100	“ “ “	“ “ $200	20 “
“ “ fourth	$100	“ “ “	“ “ $300	30 “
“ “ fifth	$100	“ “ “	“ “ $400	40 “
From $500 to	$1000	per month consumption	“ “ $500	50 “
Excess over	$1000	per month consumption	“ “	60 “

The first three charge a fixed sum per h. p. or per kw. connected per month, plus a power consumption charge. Winnipeg has a system of charges based on hours of demand. However, if plotted, the power rates of Regina would be nearly the same as those of Saskatoon, while Moose Jaw rates would likely fall between Saskatoon and Edmonton as shown in Figs. 4 and 5. The off-peak schedules of the different cities were not plotted.

The Kamloops power rates could not be easily plotted.

These rates were plotted in curve form, not particularly to show absolute values, but to show how size of plant, cheap hydroelectric power and cheap fuel affect the cost of power to the consumer. Low first costs of plant and low fixed charges have an appreciable effect as can be seen by comparing these curves with the figures given in Tables V and VI.

The rates for Calgary are the lowest in the West with the exception of Winnipeg, due largely to the low cost of hydroelectric power.

The Medicine Hat plant serves power consumers almost entirely and its lighting rates are therefore high.

Edmonton rates should be reduced when the obsolescence charges are fully met.

Reductions may be expected in the rates of the other cities in proportion to the growth of the plant load, (for all of the power plants are now operating under normal loads) and with improvement of their load factors.

A comparison of Tables V and VIII shows that in many cities rates for power are quoted at less than net cost and often at less than production cost. It is held that power loads are necessary to build up the load factor and to increase the total output of the plant. In this way the cost per unit will be reduced. On the other hand, it is evident that if such consumers do not pay their proportion per unit, of the fixed charges and other costs, then other consumers—generally those using lighting only—are forced to pay an unduly large proportion of the costs if the utility is to meet its expenses. In such cases there is discrimination in favor of the large power users, who enjoy special privileges at the expense of the smaller consumers. This is unjust and the public can demand that this practise be stopped.

Another argument is that a low rate is quoted by the city as an inducement to industries to locate in its limits. It is maintained that any loss resulting from this low rate is more than offset by the benefits the city receives from having such an industry in its boundaries. This in the abstract amounts to a bonus to such an industry. The injustice of this plan lies in the fact that only the consumers of electricity pay this bonus, which logically should be paid in taxes by all the property owners if the municipality desires to give such aid to an industry.

But on the other hand, the costs of service, of meter readings and of office work are much less in the case of the large consumer than where the demand is small, and it is perfectly reasonable that he should be quoted a lower rate on these grounds. Nevertheless it is difficult to justify rates that do not cover the total operating costs plus fixed charges plus a portion at least of the distribution and office expenses. If the rates are based on service charges, it is proper for the large consumer to pay an equitable share of capital charges for his maximum demand on the station just the same as in the case of the smaller user.

The Winnipeg power rates deserve notice. The base rate does not vary with the size of the electrical demand, but varies with the duration of this demand per month. The logic of this rate is sound for it is evident that no consumer using power for over 50 hours per month could have this all on during the peak load hours. Thus a consumer using all his power for 200 hours per month provides a load two-thirds of which under any circumstances, must occur during off-peak hours. The large consumer only benefits by the liberal discounts given along with the rates.

The primary lighting rates in these Canadian cities have apparently been adjusted to favor the small consumer. The distance from oil-producing territory makes kerosene an expensive commodity. Hence in many cities, even the smallest householders find it not only more convenient but more economical to use municipal electric light than to burn kerosene lamps and these consumers, especially in those cities with minimum charges, provide a very considerable portion of the total revenue. In general the primary rates of cities in the United States exceed those of cities of similar size in Western Canada. Only a complete investigation by a public utility commission would show whether or not the small consumers are unduly favored in the latter cities.

A survey of the rates of privately owned plants in cities of similar size in Wisconsin as reported by the Railroad Commission of that state and in Massachusetts as reported by the Board of Gas and Electric Light Commissioners, indicates that in general their rates are considerably higher both for light and power than in the municipality owned utilities of these Canadian cities.

While it is possible, as already pointed out, that in some of these municipal undertakings adequate provision is not made for depreciation and obsolescence, in most cases this could be provided out of surplus without appreciably affecting rates. Why then should the Canadian cities be able to provide such rates? In the first place these utilities have no promotion or franchise expenses to capitalize and on which to earn a return. Nor have they capitalized "going value" or "good-will." In these particulars they have a decided advantage over the cities with privately owned plants.

Another feature is that in adjusting rates in privately owned plants, present value must necessarily be considered. In a growing city, property increases rapidly in value and a private company is rightly entitled to earn money on the present value of its holdings or otherwise it would not pay the company to retain the property. In municipal enterprises any increment in value belongs to the city and does not need to be capitalized for rate making, although increasing the available assets of the utility and thus proving of value in issuing securities.

A third factor is the matter of returns on the investment. The Wisconsin Commission has ruled that companies are entitled to rates of from 7 to 8 per cent on their investment in order that capital may be induced to invest in them.

The Board of Gas and Electric Light Commissioners of Massachusetts report for 1914, dividends in privately operated electrical utilities ranging from 5 to 22 per cent. It is probable that those earning the biggest dividends are undercapitalized or that the plant has been largely built out of earnings.

The Canadian municipally-operated utilities are financed by debentures bearing from 4½ to 6 per cent interest. It is at once evident that there is an appreciable saving in this method of financing over that of private companies. This saving results in correspondingly lower rates to the customers of these utilities.

Finally the municipally owned utilities do not require a set of directors and higher officials who often draw extravagant salaries taken from earnings. The executive administration of these utilities is generally quite simple and efficient, the only high-salaried officials being the commissioner, the superintendent and the electrical engineer. Furthermore, it is not possible to milk the municipal utility for exorbitant fees for promotion and legal purposes and for receiverships and reorganizations. There is also no chance to manipulate earnings by means of subsidiary companies who supply power, own roadbeds or have other favorable concessions that enable them to take the cream from the profits of the utility itself.

CENTRAL HEATING SYSTEMS

In the prairie provinces heat and pure water for cities are absolute necessities, the first to permit existence in cold weather, the second on account of the pollution of much of the local water with alkali or river mud. Light is less necessary than the other two. The people of these cities have cooperated in the establishment of their municpal plants to supply light and water but aside from the natural gas supply at Medicine Hat, have taken no steps to cooperate in the economical generation and distribution of heat. They do not seem to appreciate at full value the ease with which such a central heating system can be installed and operated, and the satisfactory financial and economic results that would be obtained from it. However, it must be kept in mind that a large portion of the population emigrated from Europe where such cooperative methods of heating are unknown. Hence this system is not understood and its full value has not been appreciated.

Hence none of these municipal plants has made any attempt to develop exhaust steam central heating in connection with its power plant. This would appear to be a promising field to exploit in those cities where coal is expensive and the winters long and cold, as in Saskatchewan. Where the power plant is centrally located, it should not be a difficult proposition to build tunnels at least through the business section for steam pipes, electric wiring, etc. and to derive a very profitable return therefrom. It should be possible to provide heat to consumers at a lower cost than by present methods. The conditions at Saskatoon seem to be favorable for this purpose as the old reciprocating engine could supply much of the exhaust steam needed. The old station at Regina could also be utilized for similar purposes and need operate only during the heating season.

GENERAL REMARKS

The municipal electric light and power utilities of these Western cities have on the whole been run efficiently. Their rates are in general fair and reasonable and compare very favorably with those existing in cities of the same size in the United States where private corporations have control.

The public in these Western cities takes a great interest in all utilities and this in a large measure has made them keep up-to-date in equipment and organization. The economic effects of the low rates have not become apparent largely because the real estate booms and inflated land values have offset the benefits of these rates.

Mistakes have been made in the past in the location and construction of electrical plants and in the selection of machinery. Most cities now have comprehensive plans prepared for plant extensions and only radical changes in prime mover designs would seriously interfere with carrying these out. The introduction and development of the steam turbine was such a change. At present, however, it does not seem likely that another new form of prime mover will be produced for a while at least.

It was a difficult matter to form any definite conclusions as to the character of service rendered by these municipally owned utilities. Since the war broke out, their electrical loads have been light and therefore they have been able to give excellent service as regards voltage control, lack of interruption, etc. It was therefore necessary to make inquiries over a period of years and these developed some interesting facts.

During the period of rapid growth in these cities the councils of the time were so engrossed in street extension, pavements, water projects, etc., that they could spare but little attention or funds for electrical plant needs. In consequence the plant was allowed to become overloaded from lack of sufficient equipment to properly handle natural increase of load. A series of interruptions in service would forcibly call the attention of the public to the critical conditions existing in the plant. Then a demand would be made for instant action and machinery would be purchased in many cases solely on the speed of delivery without particular attention being given to the ultimate station plans. This phase of municipal operation could be corrected by a utilities commission, which would have authority to regulate service before extreme conditions existed.

The administration of these utilities as has already been pointed out, is in the hands of either a commissioner, a superintendent or an electrical engineer and when these are free from interference on the part of the council, the utility is administered well and economically.

In a recent discussion of municipal plant operation in Oklahoma, Prof. Bozell makes the following statement:

> In practically every case where a cash surplus of any size was revealed, as well as in every case in which efficient operation and an intelligible accounting system were found, there proved to be someone in the munici-

pality who was devoting a large part of his time to the handling of the plant without any charge to the municipality.

A review of the utilities of Western Canada does not reveal any such condition to exist in these cities, for with the exception of Kamloops, the municipalities are large enough to employ competent superintendents.

In Manitoba, a public service commission has authority over public utilities. A similar commission has been appointed in Alberta since this investigation was made. But, at present there is no executive board in either British Columbia or Saskatchewan with such authority. Hence the municipal enterprises of these provinces are at the tender mercies of the common councils of the cities and towns. Such bodies have frequently in the past committed their municipalities to ill-advised extensions. It would seem advisable to have an executive board in each province organized along the line of the railroad commission of Wisconsin, who would have the necessary executive authority and with duties about as follows:

(a) To pass on all new extensions and expenditures of public utilities and to see that funds are spent on the improvements for which they are set aside.

(b) To receive and approve financial reports of the utilities and to adjust sinking funds and depreciation charges.

(c) To adjust equitable rates without discrimination and to scrutinize the disposal of surplus.

(d) To establish standards of service that the utilities can meet and that customers can reasonably demand. Owing to changes in the state of the art, these standards require frequent revision. Such changes usually result in improvement of service frequently at a lower cost.

(e) To collect engineering data and to provide engineering assistance to municipalities undertaking new enterprises. The commission should also be empowered to pass on the plans of all new projects.

(f) To advise with municipal authorities regarding the floating of debentures and to assist in a material way in marketing these. In many cases those in charge of the financial affairs of small towns have never had experience in these matters and competent assistance and advice would be most welcome.

Such a board should consist of only highly trained men experienced in this work and should preferably have three members, an engineer, an accountant and an economist. On no account should a man with a political record be allowed a place on such a board. In fact, it might be even advisable to appoint men from outside the provinces who would thus be free from local prejudices and political affiliations. The board could act in an advisory capacity for municipalities on all matters dealing with utilities. Such control would have prevented many of the mistakes made in the needless extension of utilities and would have insisted on sound financial conditions in all utilities.

The establishment of such a commission would not necessarily curtail the control of any municipality over its own utilities. The local councils would still have the power to regulate rates, etc., subject only to review by the utilities board on appeal by one of the local consumers.

A further function of such a board would be to exercise executive control over the surburban and interurban activities of the utilities. Difficulties frequently arise in regard to the control, the rates and the service outside the municipal boundaries and beyond the control of of the city's authorities. These could be equitably adjusted by the commission.

Another useful activity of such a commission would be the standardization of the accounting systems of the various utilities. The difficulties met with in preparing the summary given in Table IV and the difference of opinion as to its accuracy as regards distribution of expense, make evident the need of such standardization if comparisons are to be made between the costs of different cities. Several of the public utility commissions in the United States have standardized utility accounting in a satisfactory manner.

Such mistakes as have been made by the executives of these municipal undertakings have not been intentional nor due to carelessness. Generally these errors were in connection with matters with which the official had no previous experience and at the moment lacked competent counsel. The inauguration of a friendly spirit of cooperation between utility executives and the proposed commission would do much to materially improve matters in the future, for the commission could be called on for consultation whenever new difficulties were encountered.

CONCLUSIONS

In the preceding discussion, emphasis has been placed on certain principles that should be applied to the organization of municipally owned utilities. These may be briefly summarized as follows:

(1) The utility should be entirely self-supporting, and consumers should be charged such rates that the returns will meet all the usual expenses of

the business but will not provide balances to be used in extensions or improvements or to offset losses in other departments.

(2) The utility should be under the direction of a single commissioner or superintendent holding office on good behavior and who should be given a free hand to develop the utility without political or civic-council interference.

(3) The utility should bear its portion of the cost of general municipal government through assessment and taxation. The latter should be paid from revenue and the rates to consumers should be adjusted to provide these funds.

(4) The utility should be financed by means of serial bonds instead of long term debentures and all such issues should equal only the life of the improvement they are intended to cover.

(5) Obsolete machinery should be written off the books at once, either by using surplus funds or by increasing rates. Depreciation or replacement funds should be set aside from revenue to provide for the renewal of the plant when worn out.

(6) An emergency reserve fund of moderate amount should be accumulated out of surplus to meet extraordinary contingencies.

(7) All improvements and extensions should be financed by additional bond issues and not from surplus funds.

(8) The net surplus of the utility should be distributed in the form of proportional rebates to consumers.

(9) A public utility commission should supervise the finance, accounting, rates and administration of the municipal as well as privately owned utilities of each province.

The preceding discussion of facts and conditions connected with the organization, financing, operation, rates and service of the electric light and power utilities of these cities of Western Canada, leads one to the following conclusions in regard to the general criticisms of municipally owned public utilities stated in the opening paragraphs of this paper.

(1) The rapid growth of these cities has forced the executives of their utilities to make frequent extensions to their plants which on the whole are therefore well equipped with modern and efficient machinery and provide satisfactory service.

(2) Rates for lighting and power are as low and in many cases lower than those in force in cities of similar size in the United States and are reasonable charges for the service rendered.

(3) Accounting as a rule is now carefully done and the utility's finances are isolated from other accounts. Some of the methods of financing as regards debentures, sinking fund, depreciation and surplus are open to some criticism as shown in the preceding discussion.

(4) Most of these utilities have been fortunate in having good organization with competent executives.

(5) There may be isolated cases where politics has influenced the management of the utility. But there was nowhere evidence of the

application of the "spoils system" to the municipal plants and in the majority of cases, the utility has been tolerably free from political interference.

It must not be assumed that this paper is an endorsement of public ownership. An effort has simply been made to present the facts that came to hand during visits to the various cities, without bias either for or against municipal ownership. If this article seems to favor municipal ownership or control, it is only because the facts as they were found, pointed in that direction. Such criticism and suggestions as have been made in this discussion are offered in a friendly spirit and in the hope that they may prove of benefit to these Western cities. In conclusion, the writer wishes to acknowledge the great assistance rendered him by the officials of these cities in the collection of data and in the inspection of plants and systems.

DISCUSSION ON "THE MUNICIPALLY-OPERATED ELECTRICAL UTILITIES OF WESTERN CANADA" (CHRISTIE), NEW YORK, FEB. 8, 1916.

Philander Betts: I think of all those who are opposed to municipal ownership, those that know most about it are the engineers and operators, etc., of utilities. Among those who favor municipal ownership and operation, I think we will find only a small number of engineers. The others are economists, publicists, politicians, most of whom are honest, but the list includes demagogues and others whose arguments are based on personal benefit.

In the observation of the operation of utilities in the State of New Jersey during the past five years, and during the past three years more particularly, since the Commission has prescribed classification of accounts and has called for annual reports from municipally-operated utilities, there has been an opportunity to observe the operations of these utilities, and what stands out most markedly is the chaotic way in which they are operated and managed. The condition in Western Canada appears to be quite different, and brings out some things that I think we have all got to take account of.

I think the paper sounds a word of warning, in a way, and I want to point out what that is. In the first place, municipal financing is based on a theory different from the theories on which our ordinarily operated public utilities are financed. The publicly owned utility or project of any kind is financed on the theory that it will suffice for this generation or for the life of the project, and that a scheme of financing must be worked out so that any bonds issued to pay for that project must in some way be taken up by the time that project is worn out, in this way leaving the future generation free to finance its own projects and determine for itself whether it will renew them. This applies to projects other than utilities, and includes roads, school houses and other public matters.

In regard to public utilities which are privately owned, we are working on a theory that these things go on forever, perhaps not as they are at present constructed, but in some form, and our financial schemes are based on the idea that they will go on forever, that they must be maintained and replaced as they become worn out, and that the capitalization needed to construct them continues and is not entirely retired at any time.

This latter method of financing, if all other things were equal, would really mean cheaper rates, if the capitalization is not retired. That is a mathematical problem, capable of demonstration with a little trouble, but not a matter, I think, which is worth while going into now.

In order to know definitely whether municipally-operated utilities are any better than privately-owned utilities we must have proper methods of financing, proper methods of recording the various transactions involved in the construction of the plants and of recording the transactions involved in the operation of these plants, and the accounting systems must be imposed by some power superior to the municipal authorities. In New Jersey our greatest difficulty has been to place the responsibility.

Last year twelve of the municipalities in New Jersey operating water departments were summoned by the Commission to explain why they had not furnished a full report of the operations for the preceding year. In each case the Mayor or the Clerk of the Council, or some official, tried to throw the responsibility on some one else, and it developed that almost all municipal operations are conducted on what to a business man is an inexcusably chaotic basis. Receipts, revenues from the operation of the municipal utility, are considered and handled like any other municipal revenue. They are taken up, handled and carried along in the same accounts with taxes, with license fees, and with other revenues. The costs of operating a municipal utility, on the other hand, usually come out of the proceeds from taxes.

Without a proper system of accounting no one knows whether the system is operating successfully or not, from a financial standpoint, and to my mind that is clearly improper. There are a few cases that stand out in considerable contrast, in which the utilities are operated as a business proposition, in which the revenues, expenses, and all the accounts are handled through one department in such a way as to show whether the project operates at a gain or a loss.

In making a proper comparison, however, Prof. Christie has called attention to the matter of taxation. To show how important it is that all municipal utilities should pay their taxes just like any other utility, I want to call attention to a condition in one of the counties in New Jersey, consisting of about twelve municipalities. Ten of these municipalities own their own water departments and two of these municipalities are served with water by private companies. In the system of taxation in force in New Jersey a part of the tax money furnished by the municipalities goes to the county to support the operations of the county and, therefore, a tax collected in one municipality is of benefit, in a way, to all of the municipalities within that county. If the water companies in these two out of the twelve municipalities pay their full share of taxes a large portion of that tax is expended for improvements in the other ten municipalities.

That condition is recognized by many of the municipalities in New Jersey, and has led to a system of trading, by which the municipalities have said, or a particular municipality has said, to the water company—"we don't want you to pay taxes and in turn we will not pay for the municipal water service that we get for our City Hall and School Buildings and Fire Houses, and in many cases for the fire hydrants. We will just exchange credit for these things, and we recognize that we as a municipality, and our citizens within our municipality will be better off, we will keep within our municipality the full amount of money that would be paid by that utility in the form of taxes."

Is that a proper state of affairs? I think not, and I think that shows the necessity for every utility to pay its own taxes, whether it is municipally operated or not, provided any utility is to pay taxes, and it appears to be a well established thing that all property is to be taxed as we now understand these things.

There is another feature which is very important in the operation of a municipal utility. In a few cases in this country—Anderson, Indiana, is one—the service of the utility is paid for at regular rates. Every bit of service furnished by the utility, service for the lighting of the school houses, of the police stations, and other municipal buildings should be paid for in accordance with the regular rate. Street lighting service should be paid for, taxes should be levied, actually, for that specific purpose, and credited to the utility, just as they would be if that utility was operated by a private corporation.

A municipally-operated utility ought not to confine itself, if it is to do its proper duty to the public, solely to any matter of street lighting. It ought to be treated like any other utility, considered as a natural monopoly, and not only be allowed to, but required to furnish every class of service needed in that municipality. It ought to do the lighting, other than street lighting, provide all the necessary industrial power, and all current required in the municipality for any ordinary purpose.

Now, let us consider this question: If every utility was treated exactly the same way, financed in a proper way, kept its operating accounts in a way to show the real result, and if there was an equal amount of efficiency displayed in the financing, construction and operation, then would there be an advantage to the municipality that owned its own utility? There might be in this one way—in the regulation of rates we are often confronted with claims for value which have no basis in connection with the investment. The investment itself might be made up or considered as of two parts, actual investment in the physical property and everything that goes with that, and the investment, just as much an element of cost as anything else, that comes from the lack of earnings in the early years, lack of profits, and the unearned depreciation which must not be forgotten.

Instead of setting up a claim for a value as a going concern, which is the value that ought to be taken into account in a case where one purchases a property as a going concern, or where property is sold,—in claiming a value of that kind, I think we get away from the proper basis, and that is the investment;—a just consideration of the investment will take into account not an element known as going concern but an element that may be about the same, mathematically. It may be far in excess of any so-called going concern value or it may be less, and that is "cost of establishing the business." That includes this lack of earnings in the early years, lack of profits as time goes on, and this unearned depreciation due to the gradual and growing obsolescence of plants and the necessity for replacing them before a reserve has been accumulated to provide for that purpose.

If the claims set up by the company extends that far and no further, then there can be no advantage whatever that can accrue from municipal ownership, provided that in connection with ownership by municipalities the financing and accounting and all operating conditions shall be carried on in exactly the same way that must be done by any efficient business organization carrying on the same class of work.

Henry G. Stott: The fundamental point, it seems to me is this.—Is there any difference between a municipally owned plant and a privately owned plant? Either a municipality or a private individual can buy efficient apparatus, one can construct as efficient a plant as the other. The next question is—What are the objects to be gained under the two classes? In one case, theoretically, the municipal ownership plant is constructed to give service at cost. In the other case, of the privately owned plant, or incorporated plant, admittedly the object is not only to give service, but to make a profit. Under these two plans it would look as if the municipally owned plant ought to give the cheapest service, other things being equal, but actually what do we find? We find this, that in the municipally owned plant as a rule—I am talking about conditions in this country—the plant becomes the prey of politicians.

In one case there is a basis of trading political preferment without any desire to earn dividends. In the other case there is an actual and avowed desire for gain. There is no secret about it. The privately owned corporation exists to make money for its stockholders, and therefore must be operated efficiently. These are the two fundamental differences.

If we can get away in the municipally owned plant from the idea that every alderman or councilman or politician has a right to send men around for this, that and the other job in connection with the municipally owned plant, and if there are no jobs open for them, the jobs must be made, with the resulting demoralization of the staff, then the municipally owned plant will be equally efficient and equally well operated as the private plant—there is no doubt about that—but we have no symptoms of that change in method at the present time.

The biggest problem in the electrical industry today in connection with the business of supplying power, is the question of obsolescence. In the case of the average plant today the greater part of the machinery becomes obsolete in from ten to fifteen years; very little of it lasts fifteen years, the average is about twelve years. I know of one case where a piece of apparatus which cost a quarter of a million dollars twelve years ago was scrapped recently and sold for $8000. We should establish an obsolescence fund. It is a proper charge against the cost of making power, because we know as certainly as it is possible to know by the history of the past that in the future there will be further developments, so that during the course of every decade or a little more, we must completely revolutionize our plant. This is a difficult thing to have recognized in any municipality today, the fact that a charge for obsolescence is a proper one to make.

If we could, as Mr. Christie suggests, have one man put fully in charge of a plant and make him absolutely responsible for the operation and for the financing of it, and have every one connected with the plant follow his instructions without outside interference, then I see no reason why the municipally operated plant should not be operated equally advantageously with the ordinary privately owned plant. But they cannot be upon any equality, until we get rid of the idea in this country that the municipally operated plant is the means of passing around favors for the politicians, and until we put it on the basis of actually earning a revenue for the stockholders who are the tax payers of that city.

R. P. Bolton: Mr. Christie has almost wholly disregarded an essential element which is rarely offered and generally almost impossible to secure in regard to municipal undertakings. This is not only the rate or cost, but the extent of the contributions made to the income of municipal utilities by other branches of the municipality. The paper contains but one slight reference to this subject.

My investigations in Winnipeg and a number of cities in Ontario, have convinced me that municipal officials generally guarantee either an excessive use of electricity or charge high rates for energy supplied for municipal purposes. In fact I have found instances where the amount guaranteed has deliberately been made sufficient to secure the appearance of a surplus upon annual operation.

I can offer a particularly definite illustration of this in the operation of the municipal hydroelectric system in the City of Toronto, from the report of which for the year 1914, I take the following figures:

Out of a total income of $1,501,291, no less than $562,353 was derived from the payments made for the lighting of streets, of public buildings, and for power used in municipal water supply, pumping, etc. The total cost of the electric energy supplied, both for municipal and for all commercial purposes was $324,236 while the charges paid for street lighting by the municipality to the electric system amount to $364,214. For municipal power purposes, the sum of $157,700 was paid. I learned that the cost of electrical operation of the pumping service was in excess of that for steam operation, and that the chief engineer of the water department resigned his position several years ago following the disregard of his protest against the change of system made necessary by the attempt to supply electric service to the municipal pumping system.

So far as street lighting is concerned, the cost for 1914 may be compared with the cost prior to the establishment of the municipal system, when the city was lighted by the Toronto Electric Company at a total cost of $135,000. Thus, in about five years of operation, the cost of street lighting has been nearly trebled.

The result of these excessive contributions by the municipality was, for the year 1914, to bring about a surplus amounting to about 4½ per cent of the total income which, as is evident from the foregoing figures, is not real but merely apparent.

The total energy used for the year 1914 of this municipal system was as follows:

For residential and commercial lighting, kw-hr.	13,752,500
For commercial power, kw-hr.	20,724,800
For municipal purposes, light and power, kw-hr.	50,115,000

It may be conceded at once that the large quantity of energy absorbed for municipal purposes warrants a low rate per unit, but it is the total contribution which brings about the effect upon the municipal accounting.

In making investigations in Winnipeg, I found that very similar conditions obtained there. I was informed at the time of my last visit that the city pumping department was being charged a higher rate for energy than was a commercial undertaking in the immediate vicinity, although the city pumping was an off-peak load and the commercial operation a twenty-four hour load.

The situation in Winnipeg has not been quite fairly reported to Mr. Christie, judging by his description of it. The private corporation to which he refers had been in operation since the year 1892, and, during the greater part of its existence no dividend had been earned upon the capital invested. At the time of the commencement of the agitation for a municipal electric system upwards of $4,000,000 had been invested by this company, upon which only 5 per cent was earned, while the arrears of unearned dividend at that time amounted to nearly $300,000. The agitation was not directed by any necessity for a supply of very cheap power, since power was at that time available for industries at rates as low as they are today. The company had also voluntarily reduced its rates for domestic service and the maximum charge for the minimum service was the ten-cent rate.

In point of fact, the agitation for a flat three-cent rate for domestic service in which the city has become involved was started by cetain ill-informed persons for political purposes. This unfortunate local agitation has resulted in a total investment of nearly $7,500,000 and the bonded indebtedness of the city has been increased 33 per cent by the process. As in the case of other cities described by Mr. Christie, lying further west, the result has been disastrous to the credit of the communities, and in my judgment, the present unfortunate situation in western Canada is largely attributable to this unnecessary class of investment. The same remark applies in a degree, to cities in Ontario.

The extravagant investments of these cities and particularly of Winnipeg, are due to an ill-informed faith in hydroelectric generation of energy, involving expense far in excess of that of first class steam power plants, and presenting very often great difficulties in the way of any future radical change or enlargement. This point is well illustrated by conditions in Winnipeg, the cost of its plant per kilowatt of installed capacity being $132. A first class steam plant might have been built at $50 per kilowatt of capacity. The fixed charges on the difference of $82 upon the output recorded for the year 1914, amount to 0.37 of a cent per kw-hr. which is equivalent to the cost of coal at the rate of 1.8 pounds per kw-hr. and at the price of $4.00 per short ton. The excess investment amounting to $2,500,000 has, therefore, little or no commercial value.

Moreover the municipal plant in Winnipeg as in other places, is lacking in stability as a result of the liability to failure of all hydroelectric and transmission systems, and is in this respect at a disadvantage when compared with the system established by the private company which has a large steam power plant in the city. From these facts a peculiar situation has arisen. Sundry consumers upon the municipal system are paying for breakdown service on the private system as a reserve, being thus put to double expense.

The State of Manitoba has established a public service commission system, one of the problems of which, as described to me by the Commissioner, was how to deal with the unfair competition established by municipally operated systems like those in Winnipeg. The various municipal systems in the province of Ontario are under the control of the Hydroelectric Power Commission of that province by which a uniform system of accounting has been established recently. In this accounting system depreciation must be provided for. No provision, however, is made for the bringing out of the extent of the contributions of the municipality toward the support of its electrical utility. I have investigated instances in which, in order to make up a prior deficiency, the amount of street lighting in a small town has been doubled in a year.

In view of this feature of Canadian municipal operations, it would seem necessary that all the facts should be known before decision as to their financial failure or success is made. Information in the paper is, as I have said, meagre, but enough is stated to indicate that the process I have described is evidently being followed. Thus, for railway services, prices are apparently charged which vary all the way from ½ to 2 cents per kw-hr. Arc lamps are charged as high as $65 and $70 per annum. In Calgary, the street lighting is charged at the rate of $24 per 100-watt equivalent. Doubtless further investigation by Mr. Christie would bring out other remarkable illustrations of the methods by which this process is pursued.

My own attitude toward municipally operated utilities is dictated by a desire for fair treatment and full consideration of the right of communities to decide whether they will pledge their own credit to effect certain results or allow other persons to do it for them, at a reasonable price. But I regard it as the first duty of the engineer to avoid deceiving himself and deceiving others. I have never been able to find that the municipally operated utilities in Canada were free from methods open to criticism as being unequal in effect and unfair in method. Until we can be informed fully upon every important phase of the subject, judgment as to the relative efficiency and financial success of the Western Canadian municipal utilities should be suspended.

Edward J. Cheney: Mr. Christie gives us a good deal of information on what can be done, but the real question is—what *will* be done—in the situation in which we are interested. When our city governments can conduct present operations in an efficient and economical manner, it will be time to say that we can take up the municipal ownership and operation of public utilities on a satisfactory basis. For whatever reason it may be, municipally owned plants in this country do not show as successful operation as Mr. Christie shows for the Canadian ones. There are some notable exceptions, but I think invariably they are due to the fact that some broad minded, public spirited citizens, without compensation, have taken charge and kept the operation out of the hands of selfish interests.

The country which Mr. Christie has studied is new. The very rapid growth of the territory is in itself favorable for successful operation. The citizens appear to be non-political and interested in general business affairs. That atmosphere is not conducive to the development of politicians or their education in the use, for selfish purposes, of publicly owned utilities.

I do not wish to appear pessimistic, but there is some indication in the paper that those conditions may be changing and it is possible that those cities may ultimately reach that unhappy stage of development, with which we are fairly familiar in this country, in which the possibilities of exploiting the public utilities are well understood and fully taken advantage of.

It is suggested that state or provincial regulation could be used to smooth out and correct the irregularities of the municipally owned plant. Now, in this state we have state regulation which theoretically controls such plants, but the trouble is to find the man or the set of men or the organization that you can control. How do you get hold of anybody you can do anything with? I know of one instance in which the electric distribution system in a certain city was in a deplorable condition. It not only rendered good service impossible, but was an actual menace to life. The matter was taken up with the men who had charge of the plant, and these men said—" Well, we would have to go to the Board of Aldermen, and if the Board of Aldermen submitted to the citizens a bond issue, the citizens would not vote for it. We have no money and what can we do about it?" What, as a matter of fact, can be done in such a case? You cannot make men, who have no money, do anything which requires the expenditure of money, and you cannot make an order directing the citizens of a city how to vote.

Clayton H. Sharp: Is it not due to the municipal trading in these cities of western Canada that the ratio of municipal bonded indebtedness to assessed valuation of property is much higher than is allowable, for instance, in any city in the State of New York? It might be interesting to have some statistics as to the ratio of bonded indebtedness to assessed valuation.

Is it not true that municipal trading is somewhat responsible for the fact that the debentures of these cities have to be sold on the market at prices at which they will pay the investor in every case considerably more than five per cent, and often as high as six per cent?

Arthur Reid: There are one or two points in the Lethbridge plant information that are not quite correct.

Prof. Christie gives the cost of plant in Table IV as $456,370.78 and the rated kw. as 2300. This value is evidently the items "land, bldg., and machinery and tools" in the auditors statement.

This is not altogether correct because $2,000.00 of the tools account would be charged to the distribution cost. Although the auditor's statement does not show an itemized statement of the amount under "land, bldg., and machinery," this amount includes the following which should not be charged to the present electric plant.

Cost of pumping plant and alterations to power house building, to accommodate pumping plant..	$53,138.00
Cost of old plant destroyed by fire.................	48,200.00
	$101,338.00

Actual cost of new plant $456,370.78 − $2,000.00 − $101,338.00 = $353,032.78 ÷ 2,438 kw. = $144.80 per kw.

He has given the rated kw. of plant as 2300 instead of 2438, if you add the capacities as given on the plates on the machines viz: 350, 588 and 1500, you will get the above figure. Lethbridge as well as Saskatoon, had a society started by myself for mutual improvement along technical lines for the departmental employees.

In addition to the reason given by Prof. Christie, for the utility being taxed on the same basis as other industries, we have always put the following reason first—The money borrowed to create the utility is borrowed on the credit of the whole city and therefore the municipality is entitled to some return for this credit.

Regarding the disposal of surplus, since the city of Lethbridge purchased the electric plant, it has always been the policy to cut the rates for electricity to produce a revenue as near the operation costs as possible and what little surplus remains is transferred to general revenue.

The reason for the above is, because the electric light and power consumers are nearly all rate payers, if not directly, then indirectly through landlords, etc.; then, if the rates are high enough to produce a large surplus and this surplus is paid into general revenue and goes to reduce taxation, the electric light and power consumers are being overcharged to help reduce the taxes on all property including that held by parties living in other parts of the world who do not contribute one cent of the electric revenue. Therefore, it appears to me, that the only fair way is for the utility to pay the same rate of taxes as any other industry and keep the electric rates as low as will produce a slight balance on the right side of the books. This is what the city of Lethbridge has endeavored to do. Of course, in following out the above, you lay yourself open to the danger of a falling off in the receipts and are then likely to face a deficit at the end of the year, but I think this should be taken care o by putting surplus that may accrue, into a contingency fund to take care of such an event.

A. G. Christie: Mr. Betts has brought out very clearly some points in financing that deserve attention. He justly insists that the utility itself should bear all costs connected with its financing and operation. Too often the equipment does not last as long as the life of the debentures.

Mr. Scott has emphasized in his discussion one of the most important essentials for success in municipal ownership, viz—one-man control. This, and the spirit of cooperation between citizens and the utilities seem to me to be the real basis for the results shown in the West.

I have had considerable difficulty in impressing on municipal officials the necessity of figuring ample obsolescence allowances, and Mr. Stott's statements in this connection will materially assist in emphasizing my point in regard to the short life of present-day machinery.

Mr. Bolton's contribution to the discussion is very timely for by introducing the question of municipal revenue to the utility, he calls our attention to a factor that in times past has been one of the greatest shortcomings of public ownership. However, genuine attempts are being made in western cities to overcome these defects by charging for all service on the meter basis. But, as is shown in the paper, several still maintain fixed rates per lamp, and are thus still open to criticism.

In regard to Mr. Bolton's figures from Toronto, I am not intimately familiar with the situation there. However, these hardly seem fair, for he considers only lump sum figures and does not present the cost per unit or the increase in the effectiveness of the lighting system. From 20 years acquaintance with Toronto, I am able to say that it has never been better lighted than at present, and this of course, takes additional power. Furthermore, Mr. Bolton apparently discounts also the rapid growth in population and extent of Toronto from 1909 to 1914.

When one discusses Winnipeg, its situation must be clearly kept in mind. The long haul from the Alberta coal fields made the cost of steam power prohibitive. Hence the people naturally turned to water power which is available in great quantity in the country to the northeast of the city. Whether Winnipeg was warranted in expending so much on its hydroelectric system is a difficult question to discuss, yet the fact remains that the electrical utility is supplying probably the cheapest electrical power in America and is earning a surplus at the same time.

In regard to Mr. Sharp's question about bonded indebtedness, I must admit that I am not familiar with New York state figures, and I do not believe that I have the necessary figures from the cities of Western Canada to make satisfactory comparisons. I believe, however, that the ratio of bonded indebtedness to assessment will be found higher in the West than in New York.

It would puzzle one to get a fair basis for comparison in regard to assessment. Some cities are under single tax. Others have cut assessments since war broke out, while others have very inflated land values on all real estate.

The high rate of interest on Canadian municipal bonds was largely due before the war to considerable doubt among British financiers of the ability of these municipalities to pay for these debentures. They failed to realize the rapid growth of these cities. On the other hand, some cities like Saskatoon started out on too ambitious a scale.

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CREST VOLTMETERS

BY C. H. SHARP AND E. D. DOYLE

Abstract of Paper

The paper shows how a voltmeter which will read directly the maximum or crest values obtained in high-voltage testing may be constituted by a combination of an electrostatic voltmeter and an electric valve. Diagrams of connection are shown and results of test given to indicate the validity of the method.

STRESSES in dielectrics subjected to alternating voltages are proportional to the maximum rather than the mean effective value of those voltages. The ordinary voltmeter which reads r.m.s. values is nevertheless the instrument ordinarily used in high-voltage testing, and the assumptions are made that the crest factor, that is, the ratio of the maximum to the r.m.s. value of the wave, is that corresponding to a sine wave, 1.41, and further, that it does not vary therefrom. These assumptions are made with the full knowledge that in the general case they cannot correspond strictly to the facts, but the lack of a suitable instrument for reading crest voltages has made it almost imperative to adopt this course. Quite apart from the ordinary deviations of the wave form of alternators from the sine curve, the variations in wave form with the load on the transformer which are encountered in high-voltage testing are often exceedingly serious and sufficient to introduce errors which are very important indeed; especially since they may be unknown and unsuspected. This renders highly desirable a suitable instrument for reading the crest values, and hence giving results independent of these variations.

As illustrations of some of the variations which occur in actual practise, Figs. 1, 2 and 3, all taken from different testing installations in practical use, are given, which with their captions are self-explanatory. Fig. 3 is particularly striking as showing a change in crest factor of 25 per cent with quite a small change in the load. It is evident that a condition such as indicated here was an intolerable one where, as was the case, a product of great monetary value was being tested on the assumption that the wave was of sine form and invariable.

An instrument is available, and is recognized by the Standardization Rules of the A. I. E. E., whereby these maximum values may actually be measured. This is the spark gap, fitted either with needles or with spheres. Without going into detailed consideration of the shortcomings of the spark gap, it may be noted that it is deficient in that it can be set for one voltage only and gives no indications, except by breakdown, of the voltage to which it is subjected. It has been very aptly said that measuring voltages with a spark gap is like measuring current with a fuse. A spark gap can be used with accuracy only where it is placed at a sufficient distance from all extraneous bodies which might influence the character of the electrostatic field in the gap. The precautions required are outlined in the Standardization Rules. The breakdown value of the spark gap is also affected by the pressure and the relative humidity of the atmosphere. The variations due to humidity have not been standardized. The Standardization Rules say "If proper precautions are observed, the spark gap can be used to advantage in checking the calibration of voltmeters when

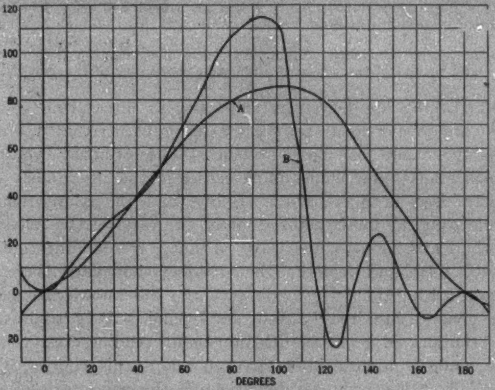

FIG. 1—WAVE FORM DISTORTIONS IN A TESTING TRANSFORMER INTRODUCED BY IMPROPER VOLTAGE CONTROL APPARATUS

A—Wave form of supply circuit.
B—Wave form of secondary of controller under load.

set up for the purpose of high-voltage tests of the insulation of machinery."

1. Sharp and Farmer[1] have described a crest voltmeter in which an instantaneous contact apparatus driven by a synchronous motor allows an electrostatic voltmeter to be put momentarily in contact with the high-voltage circuit at the crest of the wave. The voltmeter is thus charged up to the crest voltage and indicates this value. For steadying purposes a condenser is placed in parallel with the voltmeter. This apparatus can be used on a condenser multiplier from the high-tension circuit or from voltmeter windings on the high-tension transformer, or from a calibrated step-down transformer. It suffers under disadvantages as follows:

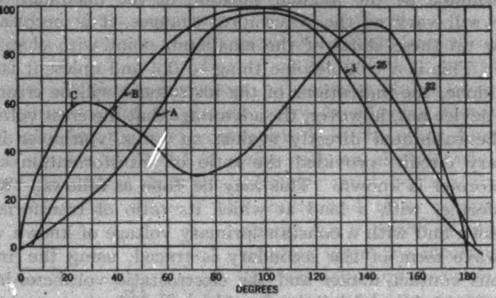

Fig. 2—Wave Form of Testing Transformer Voltage

A—No load; crest factor = 1.11 × 1.41
B—Light load; crest factor = 0.98 × 1.41
C—Heavy load; crest factor = 1.15 × 1.41

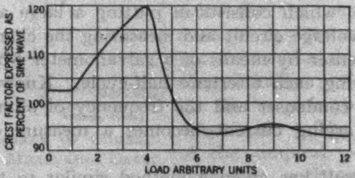

Fig. 3—Variation of Crest Factor of Testing Transformer with Load Crest Factor Expressed as Percentage of Sine Wave Value

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[1] Transactions A. I. E. E., 1912, Vol. XXXI, part II, page 1617.

(*a*) A synchronous motor is required which must be started before measurements can be made, and which will not hunt.

(*b*) The maximum point of the wave must be found by shifting the contact device.

Inasmuch as the angular position of the maximum of the wave will vary as the wave form changes, it is necessary to follow up these shifts of the maximum point with changes in load. This is a troublesome thing to do, and unless it is carefully done, the indications of the instrument will be erroneous. This device has, however, the advantage that the crest voltmeter can be calibrated directly against an r.m.s. voltmeter in the primary circuit, provided the ratio of transformation of the transformer is known. This may be done as follows: With a transformer with a load at which its ratio of transformation is known and with a constant primary voltage of known value, the wave form of the secondary is traced, using the instantaneous contact maker and the electrostatic voltmeter in connection with its multiplier. In this use of the instrument, the method is that given years ago by Ryan. From this trace of the wave form, the r.m.s. value of the secondary voltage as given by the electrostatic voltmeter plus its multiplier is computed. By comparing the true r.m.s. value as given by the primary voltmeter and ratio of transformation with the indications of the electrostatic instrument and multiplier, the multiplying factor is obtained. This is the multiplying factor which must be applied to the crest reading.

2. Chubb and Fortescue[2] have given a method of reading crest voltage, which consists in putting a large air condenser on the high-voltage circuit and measuring the charging current of that condenser by means of a galvanometer which is short-circuited during each alternate half-cycle. Knowing the capacity of the condenser and the frequency of alternations, the measured charging current becomes a measure of the crest voltages.

3. Whitehead[3] has given a method similar to the above in which mercury arc rectifiers are used in series with condensers and some form of ammeter. The connection of the rectifiers is such that the ammeter is short-circuited during one-half cycle. This method obviates the synchronous motor.

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[2] TRANSACTIONS A. I. E. E., 1913, Vol. XXXII, part I, page 739.

[3] A. I. E. E., 1914, TRANS., Vol. XXXIII, part I, p. 951.

4. Lloyd, in 1912, in discussion of the paper of Sharp and Farmer, suggested that the oscillograph might be used as a peak voltmeter. The development of the oscillograph for this purpose has been described by Middleton and Dawes.[4] In this method the length of the band of light drawn out by the oscillograph element measures the crest voltage.

The purpose of the present paper is to describe connections whereby crest voltages can be read on an indicating instrument by a relatively simple apparatus. This method takes advantage of the properties of an electric valve in allowing current to pass in one direction and in stopping it in the other direction. If such a valve is placed in series with an electrostatic voltmeter, it is evident that the voltmeter must become charged to the maximum value of the waves and must retain that charge for a period of time depending upon the insulation of the voltmeter and the valve. The indications of the instrument will be independent of the frequency of the current and of the shape of the wave, except as to its crest value. While the mercury arc rectifier has manifest possibilities as a valve, the pure ionic discharge tube of Langmuir, to which the name "kenotron" has been given, is evidently the most available form of apparatus. Langmuir has shown that in these tubes of practically perfect vacuum, the discharge is absolutely unidirectional. The apparatus is of the simplest possible character and, with proper use, entirely free from any promise of quick deterioration. The only complication is that the cathode must be heated by current, but this is provided for in a very simple manner.

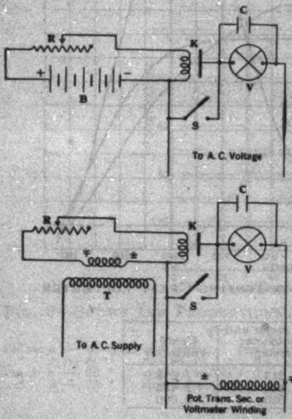

FIG. 4—DIAGRAM OF CONNECTIONS USED IN MEASURING CREST VOLTAGE

V–voltmeter; *C*–condenser; *K*–electric valve; *B*, *T*–heating battery and transformer; *S*–switch short-circuiting valve.

The electrical connections which have been used for this purpose are shown in Fig. 4. The upper half of the figure shows the filament of the kenotron excited by means of a battery of a few cells. The lower connection shows it excited by alternating current taken from the same source as supplies the testing transformers and stepped down to the voltage of the filament. The second connection is evidently the preferable one, but cannot be used where the high-tension transformer is supplied from an individual alternator with field control of the voltage supplied to the high-tension transformer.

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[4] A. I. E. E., 1914, TRANS., Vol. XXXIII, part II, p. 1185.

In the experiments here described, the voltmeter used was a pivoted one, directly indicating on a scale of volts and having a capacitance of approximately 1.6 × 10^{-4} microfarad. In parallel with this is placed a capacitance of 0.02 microfarad or more. With a smaller capacitance in parallel, the leakage of the apparatus was sufficiently great so that the indications were no longer true indications of the crest value. In other words, a sufficient reservoir of charge must be used so that the leakage is a negligible factor. With this arrangement the charge is built up to the maximum value, if not in the first half-cycle then at least in the succeeding half-cycles. This

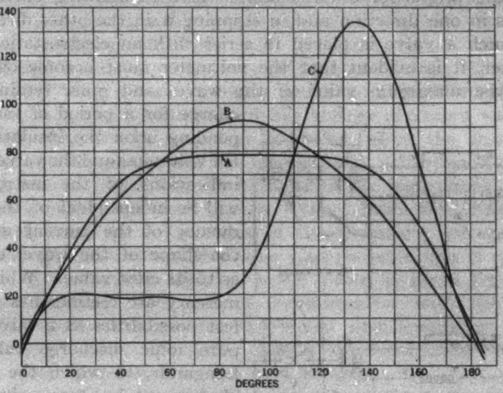

FIG. 5—BUILT-UP WAVES USED IN TESTING CREST VOLTMETER

Crest Factor by

	Wave calculation from wave form	Wave meter and dynamometer voltmeter	Crest voltmeter
A	1.218	1.213	1.218
B	1.431	1.435	1.435
C	2.040	2.020	2.090

feature is important in the use of the instrument with a condenser or high-resistance multiplier, inasmuch as it enables the valve with its voltmeter to be put in parallel with a section of a high capacitance or high resistance carrying the high-voltage current, and the result obtained is independent of the actual value of capacitance or resistance used in the multiplier, depending only upon the ratio of the impedance of the portion of the multiplier about which the voltmeter is looped, to the total impedance. The capacitance of the voltmeter itself is eliminated because of the fact that it is retained in the state of full charge, provided, of course, that the leakage is low. If the valve in series with the voltmeter is short-circuited, the voltmeter will read r.m.s. values; but these values will depend not only upon the above ratio but also upon the capacitance of the voltmeter as well.

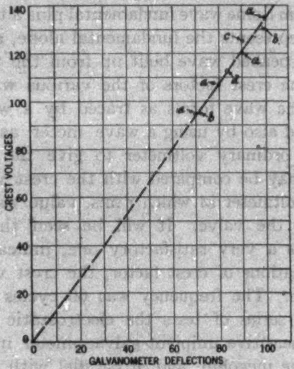

FIG. 6—SHOWS THE PROPORTIONALITY OF GALVANOMETER DEFLECTIONS TO CREST VOLTAGES

Points *a* — 60-cycle sine wave; crest factor = 1.41
" *b* — 60 " flat wave; " " = 1.30
Point *c* — 25 " peaked wave; " " = 1.56
" *d* — 25 " sine wave; " " = 1.41

If the apparatus is used directly on a step-down voltage transformer or on voltmeter coils without multiplier, the ratio of the reading of the voltmeter with the valve in series to its reading with the valve short-circuited will give at once the crest factor of the wave.

An important advantage is that the pointer of the voltmeter does not return at once when the voltage is removed. For instance, if the dielectric under test is punctured and the voltage drops, the reading of the voltmeter taken a moment after puncture has occurred will show the voltage which caused the puncture. Hence the voltmeter does not need to be watched so minutely during test as in the case when the indications follow directly any drop in the testing voltage.

This arrangement has been tested in a number of different ways, but the most important ones are summed up in the curves of Fig. 5, together with the appended table. Wave form A was built up from a sine wave fundamental plus a third harmonic; wave form B represents the fundamental alone, and wave form C represents a peaked wave built up from the third and fifth harmonics. The crest factors of the various waves were calculated from the wave forms as traced by a wave meter and were determined also by using a wave meter as a crest voltmeter and an ordinary voltmeter to give the r.m.s. values. These figures may be compared with the crest values as given by the valve voltmeter in which r.m.s. value was obtained by short-circuiting the valve. It will be seen that the degree of agreement is a very satisfactory one, indicating that with these wide variations of crest factor, the crest voltmeter gave true indications. The frequency was 60 cycles per second.

In a further series of tests the electrostatic voltmeter was replaced by a sensitive unipivot galvanometer in series with a resistance of one megohm, and in parallel with a condenser of one microfarad. The indications of the galvanometer were taken with frequencies of 25 and 60 cycles per second. In Fig. 6 is shown the relation between crest voltage as indicated by the electrostatic voltmeter plus the valve and the galvanometer plus condenser and valve. It will be seen that the relation between the two is practically a constant one, independent of the frequency of the current, which indicates that a galvanometer if looped about a sufficient capacitance may be used instead of the electrostatic instrument. Inasmuch as the latter instrument has, in some respects, less desirable characteristics than a galvanometer, particularly in respect to damping, the latter connection may be found in practise to be the more desirable one. The calibration of the latter arrangement, however, would be rather less direct than that of the former.

In conclusion it may be noted that the arrangement given offers possibilities in the matter of the study of surges. If it were connected through suitable transformers to a cable and a proper balance of valve capacity and capacitance were used, the apparatus might be adapted to trapping either a current or a voltage surge, and indicating the maximum value of the surge. With the capabilities of the arrangement for retaining its indication, it is probable the electrostatic voltmeter might be fitted to operate as an intermittent recorder, and so leave a record on a chart of the surges which have come in during a certain period of time or during the course of certain operations.

Presented at the fourth Midwinter Convention
of the American Institute of Electrical Engineers,
New York, February 8, 1916.

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THE CREST VOLTMETER

BY L. W. CHUBB

ABSTRACT OF PAPER

The demand for testing dielectric media in terms of crest voltage has resulted in several schemes of measuring high voltage. The paper mentions and compares some of the methods of high-voltage measurement and describes in more detail the crest voltmeter which has been found to be more satisfactory in commercial testing than the spark gaps which have been adopted by the Institute in the Standardization Rules. The construction, operation, accuracy and applications of the crest voltmeter are briefly described. The present Standardization Rules for the measurement of high testing-voltages recommend spark-gap methods which under certain conditions are impractical, inconvenient, and dangerous. The summary states that the spark gaps should be only a calibrating standard and a more practical instrument, such as described, the preferred working standard.

WITHIN the last few years the importance of making careful dielectric tests of insulation has been emphasized and several papers have been presented which deal with meters and apparatus for adjusting and reading the value of the testing voltage in high-voltage testing circuits. It is the purpose of this paper to describe a late modification of such a meter, to compare it with the sphere spark gap adopted as a standard by the Institute, and mention the relative merits of some of the common means of measuring high voltage in practical testing.

At ordinary frequencies, breakdown of dielectric media is dependent more upon the crest or maximum value than the r.m.s. value of the voltage wave, and for commercial testing it is desirable to have quick and accurate means of measuring voltage, which will give an indication proportional to the crest value of the testing wave under testing conditions. A meter for this purpose should preferably derive its voltage from the high-tension winding. It should be convenient, safe, direct reading, independent of atmospheric conditions and cause no oscillatory disturbances which will damage apparatus under test.

The needle and sphere spark gaps are the crest voltmeters which have been adopted by the Institute as a working standard. Careful calibrations of the spark gaps have shown that between certain limits and at commercial frequencies they give accurate indications of crest voltage when the necessary corrections for temperature, barometric pressure and humidity are made.

The possible accuracy of the spark gap, however, is not sufficient justification for its use in commercial testing, for it meets none of the other important requirements.

Other voltage measuring means, corrective schemes and types or modifications of crest voltage indicators have been described[1] from time to time, some of which meet the requirements.

Direct measurement of high-tension voltage with the electrostatic voltmeter and derivation of high-tension voltage from the primary voltage, from auxiliary ratio transformer, from tertiary coil placed in the transformer or from section taps on the secondary winding have been the most common methods used. Generally r.m.s. voltage is read, assuming the voltage wave to be sinusoidal. When testing apparatus of high capacitance and at high voltage, the ratio of transformation is affected and the wave is often so distorted that corrections for ratio and crest factor should be made. With some of these methods, and under certain favorable conditions with all of the methods, corrections can be made, but in the majority of cases such corrections are too laborious or too much in error to be worth while.

In former papers schemes of correction for crest factor have been given. Some of these have since been combined with certain improvements into an instrument especially suited to dielectric testing, equally accurate and very much more practical than the spark gap.

THE CREST VOLTMETER

Historical. In a paper[2] on the calibration of the spark gap, an absolute method of measuring the crest of an alternating voltage wave was described. By means of a rotating contactor and d'arsonval galvanometer, or d-c. voltmeter, the charging current to a guarded air condenser was integrated and from it the peak values of a symmetrical voltage calculated. In some

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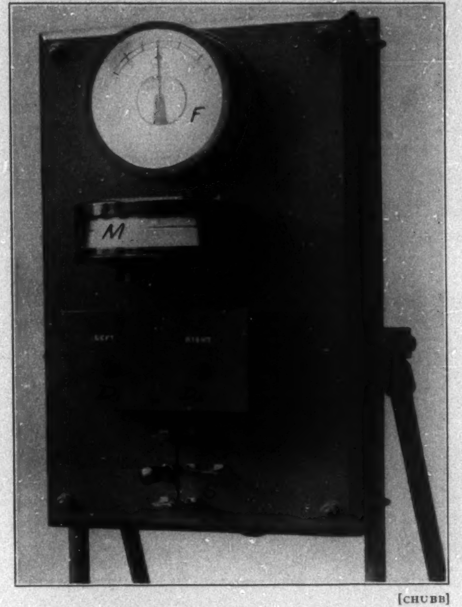
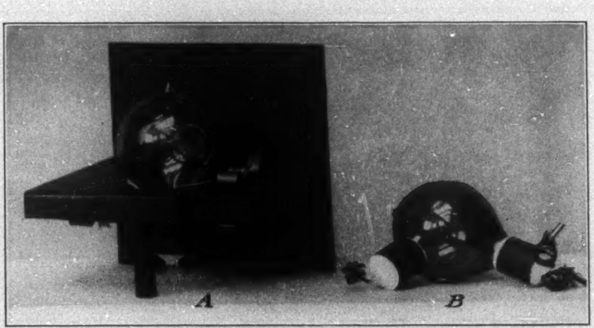
[1] Sharp and Farmer, TRANS. A.I.E.E., Vol. XXXI, 1912, p. 1617.
Chubb and Fortescue, TRANS. A.I.E.E., Vol. XXXII, 1913, p. 739.
Whitehead, TRANS. A.I.E.E., Vol. XXXII, 1913, p. 1737.
Whitehead and Gorton, TRANS. A.I.E.E., Vol. XXXIII, 1914, p. 951.
Middleton and Dawes, TRANS. A.I.E.E., Vol. XXXIII, 1914, p. 1185.

[2] Chubb and Fortescue, TRANS. A.I.E.E., Vol. XXXII, 1913, p. 739.



[CHUBB]

FIG. 1—CREST VOLTMETER



[CHUBB]

FIG. 3

A—Hot cathode valve mounted in self-connecting drawer.
B—Hot cathode valve disconnected.

later work, Whitehead and Gorton substituted mercury arc rectifiers for the rotating contactor and the Moscicki type of condenser of measured capacitance for the air condenser of figured capacitance. The change from the mechanical rectifier was made to allow measurement at high frequency and to the glass condensers presumably for convenience. In the latest modification, described in this paper, the hot cathode tube is substituted for the mercury arc rectifier and the whole apparatus arranged in compact form to make a practical measuring instrument for the testing department or laboratory.

Construction. Fig. 1 shows one type of instrument mounted on a small panel to be placed near the control apparatus of the testing transformer. It consists of a permanent magnet instrument (M) sensitive to low currents, two small hot cathode valves mounted in the drawers ($D_1 D_2$), a frequency meter (F), an exciting switch (S), and on the back the necessary wiring, resistors and two bell-ringing transformers for heating the cathode filaments of the valves.

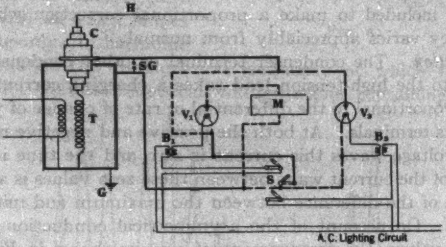


FIG. 2

The high-tension condenser terminal of the transformer or other separately mounted condenser is used in connection with the meter panel. When the transformer terminal is used, it is insulated from ground and the crest voltmeter is connected between ground and the outside flange of the terminal.

Fig. 2 shows the diagram of connections, in which T is the testing transformer diagrammatically shown in a grounded case; C is a condenser terminal used to bring out the high-tension lead (H); V_1 and V_2 are two rectifiers or valves shown in detail in Fig. 3 and having an anode of tungsten or molybdenum and a cathode of incandescent tungsten working in an atmosphere of mercury vapor, or one of the noble gases at low pressure. The filamentary cathodes are heated by the secondary current from two bell-ringing transformers, B_1 and B_2, the primaries of which are connected to any suitable a-c. lighting circuit; M is a permanent magnet indicating instrument connected in the anode lead to the valve V_1; S is three single-pole switches operated with a single handle and used to close the cathode heating circuits or short-circuit the instrument when not in use; $S.G.$ is a safety gap between the leads to the meter to protect the insulation of the apparatus in case of interruption in the supply to the bell-ringing transformers when the switch is in the working position, or in case of an accidental open circuit in the instrument wiring. The frequency meter shown in Fig. 1 is not an essential part of the measuring apparatus but may be included to make a proportional correction when the frequency varies appreciably from normal.

Operation. The condenser terminal or other condenser connected to the high-tension lead takes a charging current at all times proportional to the differential or rate of change of voltage across its terminals. At both the positive and negative maxima of the voltage waves this current is zero and the time integral or area of the current wave between these zero values is a direct measure of the difference between the maximum and minimum voltages. On account of the asymmetrical conduction of the cathode valves, the arrangement of circuits shown in Fig. 2 is such that the charging current in one direction passes through the instrument M and the valve V_1 as shown by the heavy dotted line. Current in the opposite direction passes through the valve V_2 without passing through the meter, as shown by the heavy broken line. The light lines in the figure represent the primary and secondary exciting circuits for the cathode filaments fed from the lighting circuit. When the meter is not in use the switch is thrown to the right, which short circuits the apparatus and opens the primary circuits of the exciting transformers.

The torque of a permanent magnet meter is proportional to the average value of the current passing through it, and since for waves of constant length the area is proportional to the average height of the current, it is evident that the meter will give an indication proportional to the time integral of the pulsating current through the valve V_1 and this will in turn be proportional to the crest of the voltage wave.

Calibration. The instrument is calibrated in parallel with the standard spark gaps or another standardized crest voltmeter and usually the scale drawn so that it indicates the r.m.s. value of a sine wave having a crest value equal to that of the voltage wave to which it is connected. When thus calibrated it is the equivalent of the needle or sphere gap.

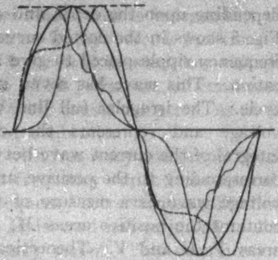


FIG. 4

Accuracy and Corrections. With the rotating contactor commutating at symmetrical zero points in the current wave, the indication of the instrument is theoretically correct with all wave shapes containing only odd harmonic components at the fundamental frequency at which it was calibrated. On unsymmetrical voltage waves containing even harmonic components (which seldom, if ever, exist in testing work) the instrument will indicate the mean between the positive and negative crest values.

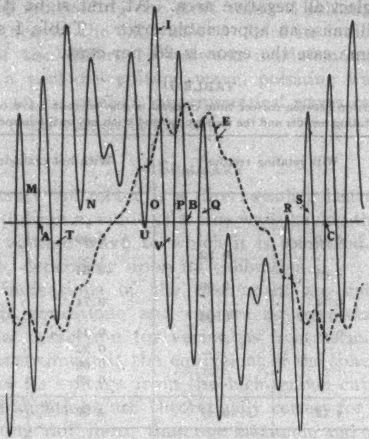


FIG. 5

With the rectifier valves, any of the waves of Fig. 4 will give the same indication and the crest voltmeter will give a theoretically correct reading. With waves having more than one maximum and one minimum per cycle there will be an error depending upon the depth and number of ripples in the wave. Fig. 5 shows in the dotted curve a voltage wave having a high-frequency ripple placed to give a large error in the meter indication. This wave has seven maxima and seven minima per cycle. The irregular full line wave is the differential of the voltage and represents the condenser current. The time integral of the current wave between the zero points, *A* and *B*, corresponding to the positive and negative crest values of the voltage wave, is a measure of the crest value. This integral contains the positive areas *M*, *N*, *O* and *P* and the negative areas *T*, *U* and *V*. Theoretically, all current, both positive and negative, between the points *A* and *B* should pass through the meter and no current between the points *B* and *C* should pass through the meter. Reverse currents cannot pass through the valves, so that the meter will integrate all positive current area and neglect all negative area. At first sight it is evident that this will cause an appreciable error. Table I shows that in this extreme case the error is 26 per cent.

TABLE I

Showing comparison between correct time integral of the current wave of Fig. 5 as obtained with the rotating rectifier and the result obtained with hot cathode rectifier.

Area	With rotating rectifier		With hot cathode rectifier	
	+	—	+	—
M	0.40	....	0.40	....
T	....	0.22	....	....
N	2.54	....	2.54	....
U	....	0.00	....	....
O	0.74	....	0.74	....
V	....	0.25	....	....
P	0.44	....	0.44	....
Q	....	....	0.22	....
R	....	....	0.00	....
S	....	....	0.25	....
Sum	4.12	0.47	4.59	0.00
Net	3.65	....	4.59	....

Tooth ripples and resonant ripples, such as shown in the voltage wave of Fig. 5, are infrequent and can be entirely avoided by the use of proper means in the transformer circuits.

In careful tests on steady circuits of different wave shapes the indications of the spark gap, corrected for atmospheric conditions, have shown agreement and duplication of points to within 0.15 per cent. Such tests seem to indicate that the capacitance of the condenser terminals used is independent of the wave shape. The capacitance is, however, a function of the voltage and increases 4 or 5 per cent between low voltage and 25 per cent over voltage. This variation of condenser capacitance with voltage, however, causes no error, as it is taken care of by the instrument calibration.

The indications vary directly with frequency and proportional corrections can be made if the frequency varies from normal. If it is desirable to eliminate frequency corrections, a calibrated shunt resistance to the meter M is used and adjusted to the indication given by the frequency meter. This complication is not justified, however, as frequency variations are infrequent and the correction when necessary is very simple.

Applications. The crest voltmeter has been found to fulfill all of the requirements of a practical instrument for dielectric testing, and for reading the crest value of pulsating and alternating voltage in the laboratory. Since its indications are a measure of the difference between maximum and minimum values of a periodic voltage wave, pulsating waves starting from zero can be read or unsymmetrical waves can be read if one of the crest values is known.

SUMMARY

1. The crest voltmeter is a direct-reading instrument, reading either the r.m.s. value of a sine wave having the same crest as a high voltage wave to which it is connected, or the true crest value, depending upon its calibration.
2. The indications of the instrument are independent of atmospheric conditions and require no corrections except a proportional correction for variations from normal frequency.
3. The instrument is the equivalent of the sphere spark gap and derives its voltage from the high-tension circuit.
4. The indications are theoretically correct for all distorted waves having not more than one maximum and one minimum value per cycle, and practically accurate for all other commercial wave shapes to be found.
5. The instrument gives a continuous indication during the application and adjustment of voltage, instead of a limiting indication similar to that of the spark gap.

6. No preliminary setting with load disconnected need be made, as the voltage may be read under testing conditions.

7. The instrument is safe, convenient, and does not cause spark surges.

8. Tests with the spark gap in accordance with sections 531 and 532 of the Standardization Rules are impractical, inaccurate and destructive under certain conditions, while with the crest voltmeter all such tests can be practically and satisfactorily made.

9. The standard spark gaps should be the primary standard for calibration only, in accordance with section 534 of the rules, and the crest voltmeter or its equivalent should be used as a secondary and working standard.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 8, 1916.

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THE VOLTMETER COIL IN TESTING TRANSFORMERS

BY A. B. HENDRICKS, JR.

FOR EXACT determination of the high-tension voltage in testing transformers, an auxiliary winding of few turns placed on the same core and connected to an accurate voltmeter has been used with success.

This method was advocated and the construction explained some years ago,* but the idea seems to be generally misunderstood, the accuracy of the result obtained being often questioned.

For precise results at all loads and power factors, it is necessary and sufficient that the ratio of the flux linkages of the voltmeter coil and the high voltage winding be a constant.

The flux here considered is the resultant flux linked with the high voltage winding, or the main flux plus or minus the leakage flux combined vectorially.

With the coil so placed, the *IR* drop is the only sensible error. This is usually small, and owing to the vector relationship under ordinary loads is practically negligible.

It is not advisable to compensate for this by the position of the voltmeter coil, as the correction would be exact for one value of load and power factor only.

The impedance of the voltmeter coil itself may be neglected.

The accuracy of the method depends entirely on the design of the transformer and the location of the voltmeter coil, and can be made almost perfect.

Ordinarily, a dynamometer type of voltmeter is used, indicating effective values. If the maximum value is desired, a sine wave of potential must be employed or, the maximum determined by other means, such as an oscillograph.

It is suggested that much difficulty may be eliminated by the use of a true sine wave generator, and the avoidance of regulating devices and transformer characteristics liable to distort the wave.

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*High-Tension Testing of Insulating Materials, A. B. Hendricks, Jr., TRANS. A. I. E. E. Vol. XXX, 1911, p. 167.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 8, 1916.

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NOTES ON THE MEASUREMENT OF HIGH VOLTAGE

BY WILLIAM R. WORK

ABSTRACT OF PAPER

A briet account is given of some experiments made to determine the relative accuracy of certain methods used in measuring high voltages.

The methods comprise the use of a tertiary (or voltmeter) coil in the high-tension transformer, the direct measurement of voltage by a crest voltage meter and the derivation of the high-tension pressure from the primary voltage.

IN MOST commercial and experimental tests employing high voltage a knowledge of the crest or peak value of the voltage is of the first importance. Often this crest value may be determined quite satisfactorily by a gap method. In other cases (dielectric tests on cables, etc.,) the use of a spark-gap is not desirable because the discharge of the gap may set up oscillations which will over-stress the dielectric thereby permanently injuring or even puncturing it.[1] There are other well known disadvantages attendant on the use of a spark-gap as a voltmeter. Several methods for the measurement of high voltages which are free from the objections peculiar to the spark gap have been used.

This paper is an account of some tests which were made with the view of comparing these methods among themselves and with a spark gap.

EXPERIMENTAL APPARATUS

The generator used is a 60-kv-a., 250-volt, eight-pole, 60-cycle, three-phase alternator with both ends of each phase winding brought out to the terminal board. In these tests the excitation was kept substantially constant at normal value and three schemes of connection were used giving three different classes of voltage waves. These schemes will be designated *Supply A*, *Supply B* and *Supply C* respectively.

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[1] *Voltage Testing of Cables*, Middleton and Dawes, TRANS. A.I.E.E., Vol. XXXIII, 1914, p. 1185.

Supply A. Windings connected in Y. Wave shape approximating a sine form. See Fig. 1.

Supply B. One-phase winding alone. Prominent third harmonic with other harmonics giving a flat-topped wave. See Fig. 1.

Supply C. Two windings connected in V. Same fundamental as *Supply B* but the third and ninth harmonics are doubled in value and the wave has a prominent hollow at the quarter-cycle point. See Fig. 2.

The transformer has a capacity of 100 kv-a. at 200,000 volts, 60 cycles. One end of the high-tension winding was grounded. The primary winding consists of four separate 480-volt coils arranged to be connected in parallel, in series-parallel or in series. The reactance drop is about 4.5 per cent, the resistance drop about 0.6 per cent. Due to the capacitance of the high-tension winding the no-load power factor of the transformer is high, varying from about 99 per cent to about 96 per cent, over the range of voltage used in these tests. The transformer had been equipped with a tertiary, or voltmeter, coil intended to serve as a means of determining the secondary voltage. This coil has taps brought out at 25 per cent and at 50 per cent of the winding. The accuracy with which the secondary voltage could be determined by the use of this coil was one of the things investigated.

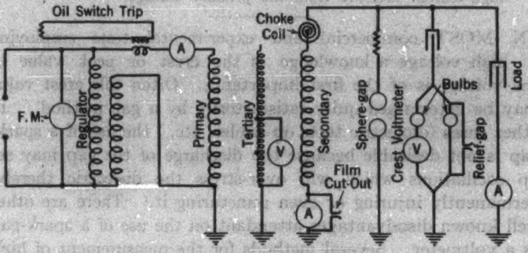
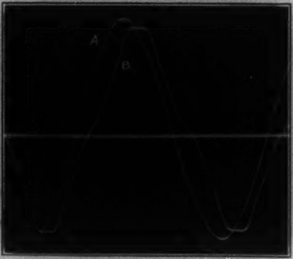


Fig. 4

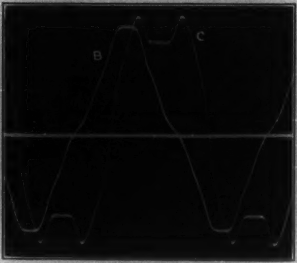
Control of the voltage was obtained by a 50-kv-a., 60-cycle induction regulator with which the pressure applied to the transformer primary could be varied from zero to twice the generator voltage in a satisfactory manner.

PLATE II.
A. I. E. E.
VOL. XXXV, 1916



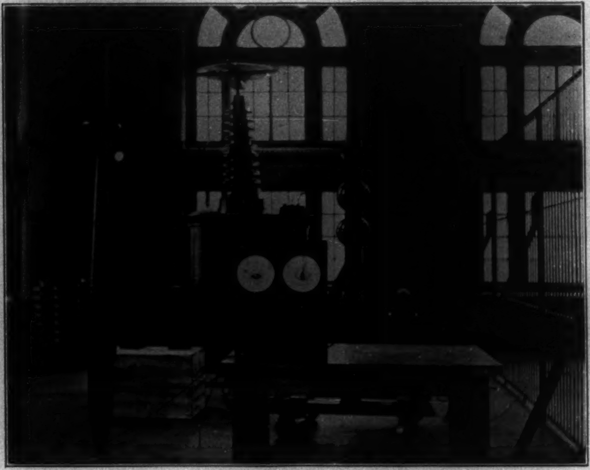
[WORK]

FIG. 1—NO-LOAD WAVE FORMS OF SUPPLIES A AND B



[WORK]

FIG. 2—NO-LOAD WAVE FORMS OF SUPPLIES B AND C



[WORK]

FIG. 3—TRANSFORMER, SPHERE GAP AND CREST VOLTAGE METER

Voltmeters of the electrodynamometer type were used, all being checked against the same precision voltmeter. The larger secondary currents were measured by a hot-wire ammeter; smaller currents, by voltmeters used as ammeters.

For the tests with condensive load, sixty ½-mf., 2000-volt condensers were available. These were used in two different combinations, *viz.*, all in series, and thirty in series, two in parallel.

The actual secondary voltage was determined by a standard 250-mm. sphere gap. The relation between the length of gap and voltage and the correction for air density as specified in the Standardization Rules of the Institute were used. Incidentally, the air density correction factor, k, for 250-mm. spheres, corresponding to a barometric pressure of b mm. and an air temperature of t deg. cent., can be expressed as a function of b and t thus:[2]

$$k = \frac{0.366\,b}{273 + t} + 0.066$$

In most of the tests the gap was set at a certain length and the voltage slowly raised until spark-over occurred; in some cases, however, the gap was shortened slowly with the voltage constant. There was little difference in the results obtained by the two methods of manipulation although the first method gave slightly more consistent results and was therefore preferred. In using the gap a set of observations was considered good only when the voltmeter (on the tertiary coil) indicated stable conditions at the moment of breakdown. Each point is the mean of five to seven trials.

DETERMINATION OF CREST FACTORS

Polar oscillograms of the voltages and currents were taken and the first six odd harmonic components of the waves were determined by a mechanical analyzer.[3] The crest values were then obtained by calculating the ordinates of the waves at a few degrees on either side of the angle at which an inspection of the oscillogram indicated the peak. The crest values thus determined from the harmonic components were checked by direct measurement of the amplitudes on the oscillograms.

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[2] Derived from Peek's eq. (4), p. 931, TRANS. A.I.E.E., Vol. XXXIII, 1914.

[3] *Electric Journal*, Feb. 1914, May, 1914.

TABLE I—SECONDARY VOLTAGE DERIVED FROM TERTIARY VOLTAGE

(Secondary pressure derived from the observed tertiary voltage and expressed as the r. m. s. value of the sine wave of equal peak.)

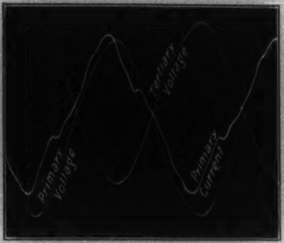
Ratio of secondary turns to tertiary turns = 1000 : 1

Test	1	2	3	4	5	6	7	8
Supply	*A*	*A*	*A*	*A*	*B*	*B*	*C*	*C*
Secondary current (amp.)	0.024	0.035	0.114	0.342	0.031	0.110	0.0306	0.323
Tertiary r. m. s. volts × 1000 = E_3	99,300	95,400	68,900	59,000	86,000	63,300	56,100	48,600
Crest factor of tertiary voltage ÷ $\sqrt{2}$ = F_3	1.026	1.024	1.011	0.968	1.127	1.067	1.017	1.212
R. m. s. value of sine of equal peak of ter. volts × 1000 = $E_3 F_3$	101900	97,700	69,700	57,100	96,900	67,500	57,100	58,900
Secondary volts by gap. R. m. s. value of sine of equal peak = E_2	103700	96,900	69,300	57,600	96,600	67,400	57,900	57,600
Per cent error by (*a*) r. m.s. ter. volts alone	—4.2	—1.5	—0.6	+2.4	—11.0	—6.1	—3.1	—15.6
(*b*) ter. volts corrected for crest factor	—1.7	+0.8	+0.6	—0.9	+0.3	+0.2	—1.4	+2.3
Figures	5	6	7	8, 13	9	10	11, 14	12, 15

An inspection of the above data shows that the tertiary voltage *corrected for crest factor* is a satisfactory measure of the actual secondary voltage as determined by a sphere gap.

Obviously the r.m.s. value of the tertiary voltage should not be used alone as a measure of the secondary voltage, when the latter is defined in terms of the crest value, unless something is known about the crest factor. The wave shape of the secondary voltage depends upon so many factors of complex relationship that it is practically impossible to predict how the crest factor will be changed by a given change in the conditions of load or supply. The condensive character of the usual load in combination with one or more of the several inductances of the system may result in the amplification of one of the higher harmonics through partial, if not full, resonance, or it may result in suppression of the higher harmonics. Magnetic saturation in the generator, control apparatus and the transformer plays an important part in wave distortion, while corona, by changing the value and phase of the current, may contribute to the effect through generator reactions.

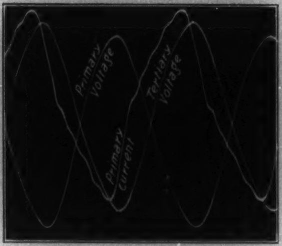
In this connection it is interesting to study the oscillograms and the crest factors of the voltage waves. In tests 1 to 4 (Figs. 5 to 8) the generator was connected to give a "good" e.m.f. wave (Supply *A*). As the load was increased the tertiary voltage wave shape changed from a peaked form to a



[WORK]

FIG. 5—TEST No. 1

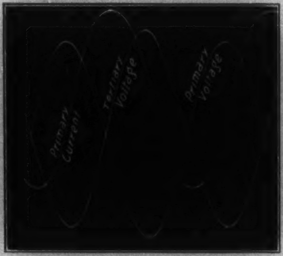
Crest factor of primary voltage = 1.421
Crest factor of tertiary voltage = 1.451



[WORK]

FIG. 6—TEST No. 2

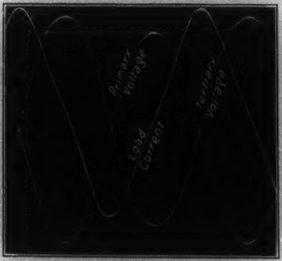
Crest factor of primary voltage = 1.434
Crest factor of tertiary voltage = 1.448



[WORK]

FIG. 7—TEST No. 3

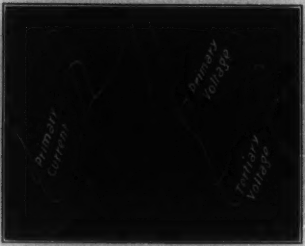
Crest factor of primary voltage = 1.424
Crest factor of tertiary voltage = 1.430



[WORK]

FIG. 8—TEST No. 4

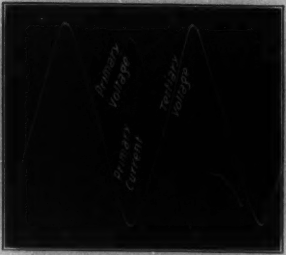
Crest factor of primary voltage = 1.414
Crest factor of tertiary voltage = 1.369
Crest factor of integral of load current = 1.373



[WORK]

Fig. 9—Test No. 5

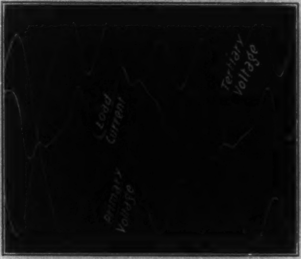
Crest factor of primary voltage = 1.581
Crest factor of tertiary voltage = 1.593



[WORK]

Fig. 10—Test No. 6

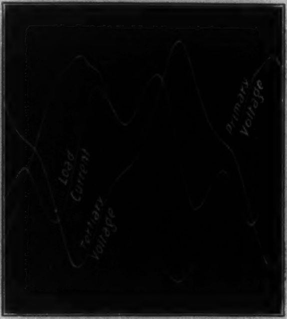
Crest factor of primary voltage = 1.474
Crest factor of tertiary voltage = 1.509



[WORK]

Fig. 11—Test No. 7

Crest factor of primary voltage = 1.399
Crest factor of tertiary voltage = 1.438
Crest factor of integral of load current = 1.528



[WORK]

Fig. 12—Test No. 8

Crest factor of primary voltage = 1.437
Crest factor of tertiary voltage = 1.714
Crest factor of integral of load current = 1.655

flat-topped form, the crest factor varying apparently as a linear function of the secondary current. In tests 5 and 6 (Figs. 9 and 10) Supply B was used. The chief impurity in these tertiary wave shapes is the third harmonic. This component was 19.2 per cent of the fundamental with the lighter load but only 6.5 per cent with the heavier load, the resulting change in the crest factor being from 1.593 to 1.509. The addition of load here reduced the crest factor. Figs. 11 and 12 (tests 7 and 8) are especially interesting in that they show great changes in wave shape and crest factor produced by simply changing the load. The chief impurity in the tertiary wave shape is again the third harmonic. Here an increase in the load lowered this component in value from 36 per cent to 24 per cent, and, what is of more importance, practically reversed its phase, resulting in a change in the crest factor from 1.438 to 1.714.

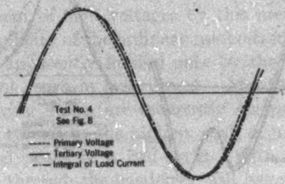


FIG. 13

The addition of load in this case therefore increased the crest factor.

There is some evidence that the tertiary voltage wave form is more likely to resemble the secondary voltage wave form than the wave form of the primary voltage. No attempt was made to determine the high-tension wave form directly, but in three of the tests this wave shape was derived by integrating the current through the condensive load expressed as a harmonic series. Dividing this integral by the capacitance of the load gave the harmonic series representing the secondary terminal voltage. Figs. 13, 14 and 15 compare the several voltage waves as mechanically synthesized from their respective harmonic series. The scale of these figures is so chosen that all the waves have the same r.m.s. value. The secondary wave shape determined in this manner is not strictly correct, on account of some corona current which was present. By integrating the whole load current and thus ignoring the in-phase component due to corona the resulting wave is made to appear to the right of the true curve; and, further, since the shift of the fundamental is proportionately greater than for the higher harmonics, the shape of the wave is affected. This error is especially noticed in Fig. 14, where the capacitance of the load was the smallest and the corona current therefore largest as compared to the condenser current. Fig. 15 shows a marked difference between the primary voltage wave and the secondary voltage wave obtained by integration, but the latter wave is in fair agreement with the wave of tertiary voltage.

These tests, few as they are, show the necessity for a knowledge of the crest factor *under the particular conditions of the test* in order to use the voltage of a tertiary coil as an accurate measure of the secondary voltage.

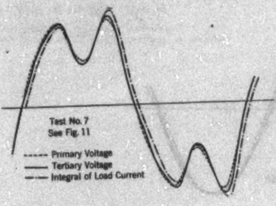


FIG. 14

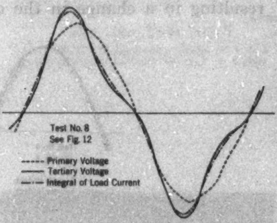


FIG. 15

SECONDARY VOLTAGE MEASURED BY CREST VOLTMETER

Crest voltmeters having indications dependent upon the average value of the charging current taken by a condenser and thereby measuring the peak value of the voltage across the condenser have been used in experimental testing.[4] In order to learn something of the usefulness of these meters under conditions prevailing in ordinary high-tension testing, a meter of this type was also used to measure the high-tension pressure in all but test 1.

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[4] Calibration of the Sphere Gap Voltmeter, Chubb and Fortescue. TRANS. A.I.E.E., 1913, Vol. XXXII, page 739.

The Electric Strength of Air, Whitehead and Gorton. TRANS. A.I.E.E., Vol. XXXIII, 1914, p. 951.

For clearness the observations are here exhibited in a separate table.

TABLE II—SECONDARY PRESSURE MEASURED BY CREST VOLTMETER AND EXPRESSED AS THE R.M.S. VALUE OF THE SINE WAVE OF EQUAL PEAK

Test	Supply	Crest voltmeter reading	Sec. volts by gap r. m. s.	Sec. volts by integ. load cur.	Error of crest voltmeter per cent
2	*A*	96,600	96,900		−0.3
3	*A*	69,600	69,300		+0.4
4	*A*	57,500	57,600	57,400	−0.2
5	*B*	96,400	96,600		−0.2
6	*B*	68,300	67,400		+1.3
7	*C*	82,700	57,900		+42.8
8	*C*	56,900	57,600	57,100	−1.2

The measurement of high voltages by this method has substantially the simplicity of the ordinary methods for low voltage, with a precision apparently limited only by the difficulties of original calibration, save in one respect. Meters of this type, employing rectifying bulbs, are inherently incapable of giving indications proportional to the highest peak of a voltage wave which has several peaks in a half-cycle. With waves of this kind the current through the condenser will have both positive and negative lobes in a half-cycle. Now the crest value of the voltage is proportional to the maximum quantity of electricity in the condenser, and this quantity is proportional to the net area of the current-time curve for one half-cycle, negative lobes counting as negative areas. The permanent magnet type instrument in series with a rectifying bulb indicates the average positive current throughout a whole cycle and thus measures the sum of the areas of all the positive lobes of the current-time curve in a whole cycle, failing to subtract the areas of the negative lobes when these are present in the first half-cycle and adding the areas of the same lobes when they appear on the positive side in the second half-cycle. The error is therefore a double one, both elements causing the meter to measure a current greater than the true average current and therefore to indicate a voltage greater than the true high-tension voltage. Test 7 (Fig. 11) shows a case in which an extreme effect of this kind was purposely obtained by resorting to the use of Supply C. Distortions of this degree are difficult to produce and are not likely to occur in practise.

An error of another kind will be introduced in the measurement unless the frequency of the e.m.f. being measured is the same as the frequency employed in the original calibration of the meter. Since with a constant e.m.f. the meter reading will vary directly as the frequency, the proper correction can be easily applied.

TABLE III—SECONDARY VOLTAGE DERIVED FROM PRIMARY VOLTAGE

(The secondary pressure expressed as the r. m. s. value of the sine wave of equal peak is assumed equal to r. m. s. value of primary pressure multiplied by the ratio of its crest factor to $\sqrt{2}$ and by the ratio of turns.)

Test	1	2	3	4	5	6	7	8
Supply	*A*	*A*	*A*	*A*	*B*	*B*	*C*	*C*
Sec. currents (amps.)	0.024	0.035	0.114	0.342	0.031	0.110	0.0306	0.323
Primary r. m. s. volts = E_1	238.4	228.5	160.0	247.9	205.4	146.6	265.7	198.5
Pri. voltage crest factor $\div \sqrt{2}$ = F_1	1.005	1.014	1.007	1.000	1.118	1.042	0.989	1.016
Ratio of turns = K	417	417	417	208	417	417	208	208
Calculated sec. volts = $E_1 F_1 K$	99,900	96,600	68,700	51,700	95,700	63,700	54,700	42,000
Sec. volts by gap, r. m. s.	103700	96,900	69,300	57,600	96,600	67,400	57,900	57,600
Per cent error	−3.7	−0.3	−0.9	−10.2	−0.9	−5.5	−5.5	−27.1
Figures	5	6	7	8, 13	9	10	11, 14	12, 15

As would be expected, the primary voltage, even when corrected for crest factor, is not, in general, a satisfactory measure of the secondary voltage, largely because the wave form of the primary voltage may or may not resemble the wave form of the secondary voltage under given circuit conditions, the difference being especially noticeable in Fig. 15. Of course the use of the simple ratio of turns is responsible for part of the error, because the internal resistance and reactance drops in the transformer are thereby neglected.

CONCLUSIONS

For the conditions of test and with the apparatus used, the following conclusions may be drawn:

It is possible to wind in a high-tension transformer a tertiary (or voltmeter) coil in such a manner that the voltage induced in this tertiary coil, when corrected for crest factor, is a satisfactory measure of the secondary terminal pressure.

A crest voltmeter provides a convenient and, in general, an accurate means for measuring high voltages, though errors can be introduced by the use of extremely distorted voltage waves.

The primary voltage, even when corrected for crest factor, is an uncertain measure of the secondary voltage because the respective wave forms may differ.

DISCUSSION ON "CREST VOLTMETERS" (SHARP AND DOYLE), "THE CREST VOLTMETER" (CHUBB), "THE VOLTMETER COIL IN TESTING TRANSFORMERS" (HENDRICKS), "NOTES ON THE MEASUREMENT OF HIGH VOLTAGE" (WORK), NEW YORK, FEB. 8, 1916.

E. E. F. Creighton: The question of the measurement of high frequency is always important, and always will be important until all the problems relative to the protection of apparatus are solved. Dr. Sharp's statement that the kenotron might be used for the measurement of high frequency is of the greatest importance. The dielectric spark lag of a perfect vacuum is practically infinite, because there are no ions present. Going down to a vacuum of something like fifteen millimeters in the usual gases the dielectric spark lag decreases to about the low value at atmospheric pressure.

It would be of interest to know in these cases how high frequencies were used in the kenotron. I had a feeling that there was not sufficient ionization in the tube to reduce the dielectric spark lag to a value which might give direct indication of the voltage. If the dielectric spark lag is not great, or if it can be taken care of at high enough ionization with the filament, there should result another instrument for measuring transitory waves in transmission lines. These waves are very difficult to get at.

At the present time we have to depend upon a number of sphere gaps connected in parallel, each one set to a different voltage. For example, in the measurement of a 13,000-volt circuit we naturally begin with the sphere gap set on double potential and go on from that to 2.5, 3, 3.5, 4, etc. In series with each one of these sphere gaps is placed a recording device, usually operating on the principle of the Branly coherer. If, however, the kenotron can be used for these high frequencies, and high potentials, it will give a simpler method of measuring and recording these transitory voltages.

F. W. Peek, Jr.: I have used one or the other of these methods in measuring high voltages at the ordinary frequencies of power transmission, high-voltage direct current, transient voltages of the duration in some cases, of a few millionths of a second, and continuous high-frequency voltages. The voltage range in these measurements was from zero to almost a million volts. I shall review the various methods and state their possibilities and limitations as I have found them in my experience.

For the purpose of discussion, the methods of measuring high voltages may be divided into three classes, (1) the spark gap; (2) the crest voltmeter consisting of a condenser and a rectifier in combination with frequency meters, ammeters, or static voltmeters connected directly to the high-voltage line; (3) the voltmeter coil, on the high-voltage side of the transformer, in combination with a low-voltage crest voltmeter.

In discussing (1), the spark gap, it is only necessary to consider the sphere. With this form of gap there is no humidity correction to make. The correction for air density is readily made. The sphere gap will measure correctly the crest voltage of the most distorted wave; it will measure correctly, direct current, high frequency over a considerable range, and impulse and transient voltages of a few micro-seconds duration.[1] In many high-voltage measurements the sphere gap is very desirable, in fact, necessary, to detect oscillations. It is invaluable in the laboratory in investigating transient voltages. The disadvantage of the sphere gap is that it must be set.

Under (2), two forms of crest voltmeters connected directly to the line have been described. In the method described by Mr. Chubb unidirectional voltage is applied to a condenser by means of a rectifier. The current and frequency are read. Good results may be obtained if the wave shape is not much distorted. Errors will result if there is insulation or corona loss in the condenser as this loss current will be read on the meter. If the voltage wave has a double peak, or a sharp peak, large errors will result. This is shown in the paper by Mr. Work where a wave of the type Fig. 14 causes an error of over 40 per cent. This is a much larger error than would have resulted if no attempt had been made at correction. In the method described by Messrs. Sharp and Doyle the rectified voltage wave is applied to a condenser. The condenser is thus charged up to the maximum of the wave. The condenser voltage is read by a static voltmeter. I have used this method directly on the line for voltages of over 100 kv. I believe it to be the more practicable of these two methods. Good results may be obtained if the insulation is very good and the condenser is of fairly high capacity. If leakage occurs the voltage reading will be too low. Thus, for high voltages, the condensers become excessively large. More will be said of the application of this method at low voltages, later. Both of these methods have extensive use in the laboratory and may be of use in some practical work. Neither will measure transients or detect oscillations.

The voltmeter coil, method (3), consists of taps brought out from a few turns of the high-voltage winding of the transformer, generally at the neutral point where the voltage above ground is zero. I have for years used a transformer, designed by Mr. Hendricks, equipped with such a coil. I have made hundreds of check tests with voltmeter coils and find that when the transformer is properly designed, and the coil properly placed, the voltage and the wave measured from the coil check very closely with the voltage and wave shape across the high-side winding. The voltmeter coil requires practically no extra equipment and involves practically no extra cost. The effective voltage may be read by a standard voltmeter, the maximum may be read by a low-voltage crest voltmeter. This crest voltmeter may be of the type described by Messrs. Sharp and Doyle and need not be large and expensive as in the case of the high-voltage types. An oscillogram of the voltage wave may be taken at any time. The voltmeter coil with crest voltmeter seems to be decidedly the best and most convenient method of measuring high voltages in practical testing where continuous readings are desired. This should always be supplemented by a sphere gap set slightly above the applied voltage to detect oscillations, etc.

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[1] F. W. Peek, Jr., "The Effect of Transient Voltages on Dielectrics." TRANS. A. I. E. E., Vol. XXXIV, 1915, p. 1857.

The methods of measuring high voltages may be summarized as follows:

(1) The sphere gap will measure correctly practically any form of voltage. It is the only method, at present, of measuring certain high-frequency and transient voltages. It is invaluable in the laboratory and in much commercial work, especially where transients are likely to occur.

Its disadvantage is that it does not read continuously. This is not always a disadvantage as the transformer may be calibrated.

(2) The various crest voltmeters consisting of condensers, rectifiers, voltmeters, ammeters, and frequency meters, connected directly to the high side of the line are useful over a limited range in practical work, but become troublesome, liable to error, and expensive at high voltage. They are not always accurate with distorted waves.

(3) The voltmeter coil in connection with a low-voltage crest voltmeter involves practically no extra space or expense and gives good results. The voltmeter coil with crest voltmeter and supplemented by a sphere gap to detect oscillations offers the best arrangement for general commercial testing.

F. M. Farmer: The problem of measuring high voltages usually involves two things, the mean effective value and the maximum value.

The first method used for measuring high voltages employs the low-tension voltage and the ratio of transformation. This method is deficient, in that we do not know anything about the ratio under varying load conditions nor have we any knowledge of the crest factor.

The next scheme developed was the use of electrostatic voltmeters on the high-voltage circuit. That gets rid of the ratio difficulties and gives us a mean effective value, but the scheme has voltage limitations because of construction difficulties at very high voltage and also because stray electrostatic field troubles become serious. Furthermore it does not give the crest voltage.

The test coil seems to be the proper thing for measuring mean effective values on the high-voltage side, but there again, some investigation is necessary to be sure of the ratio of the test-coil voltage to the total voltage under various load conditions and various dispositions of the sections of the secondary winding. Of course, in our very high-voltage testing, it is not customary to divide the high-tension winding, but in the ordinary testing transformer for routine testing at moderate voltages, the secondary winding is split up into two, four, or even eight sections, so as to be able to get the maximum kilovolt-ampere capacity of the transformer at all voltages.

The best arrangement, therefore, seems to be the use of a test coil in the high-tension winding of the transformer. An ordinary voltmeter gives the mean effective value and a crest voltmeter gives us the maximum value.

There is one question I would like to ask Mr. Chubb. Is there any variation in the capacitance of the condenser bushing? At the very high voltages is it possible that that capacity will change and thus introduce an error. In other words, does the capacity remain constant at all voltages?

Frederick Bedell: One feature of the crest voltmeters described in these papers is that it is possible by means of them to obtain an instrument reading of crest voltage without the use of a synchronous contactor. Another method for obtaining such readings without the use of any synchronous device is the method described[2] by Professor Ryan in which an impulse transformer is employed, in place of a synchronous contactor, in conjunction with the Duncan method for obtaining a-c. wave form. The impulse-transformer method makes unnecessary the synchronous contactor, but it does require the locating of the maximum reading by trial, so that readings of crest voltage are not made directly as by the crest voltmeters we have just heard described.

Comfort A. Adams: I agree thoroughly with Mr. Hendricks that it is unnecessary to go to great lengths in the measurement of peak voltage, provided you have a suitable alternator and transformer and can depend upon the voltage wave shape impressed upon the transformer, in which case an ordinary voltmeter connected to a suitably placed voltmeter coil in the transformer, will give fairly accurate results. Moreover, such an equipment is desirable not only because it facilitates voltage measurement, but also because harmonics in the e. m. f. wave are undesirable on at least two other accounts. They produce undue heating of the dielectric in some cases, and also tend to encourage transients of still higher frequencies.

We have much to learn on this subject of insulation and cable testing. In high-voltage testing very high-frequency transients of excess voltage do occur, of this there is ample evidence, and until they are under control or brought within the realm of measurement, it behooves us to go slowly. As yet the spark gap in some form is the only simple detector of transients, but even if it could be conveniently arranged for measurement rather than for detection, it would still be dangerous because of its habit of producing the very kind of a disturbance it is employed to detect. Some materials withstand abnormal transients without rupture, provided they are not repeated too often, while more fluid materials will fail and heal up many times before final rupture.

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[2] TRANSACTIONS, Vol. XVI, p. 345, 1899.

W. I. Middleton: It is very apparent from the papers that have been presented here today that the importance of a knowledge of the maximum voltage in connection with high-voltage testing is being appreciated more and more. It is not so much a question of whether the wave is distorted or not, but as to how much, and until generators giving a sine wave under a testing load are more commonly used than at present, it should be the desire of all interested to develop an instrument or instruments, that will give a direct reading in volts of the pressure at the peak, or crest, of the voltage wave.

In the early part of 1900 all of our investigations in high-voltage testing were done with the spark gap, and by its constant use under every condition of test that would arise, we were convinced that it was impossible to tell accurately what was the maximum voltage being applied to a cable under test.

In the latter part of 1911, while investigating the variations in the voltage waves of our testing set with an oscillograph, Mr. Dawes and I decided that as it was the peak of the wave we were interested in rather than its shape, an instrument much simpler than the oscillograph could be made, and in April, 1912, a working model of our instrument was being used in our factory.

The authors show some badly distorted waves obtained under testing conditions: We have experienced considerable difficulty from just such waves.

Fig. 1 shows a voltage wave obtained from a single-phase generator when it was supplying power to a step-up transformer, to the secondary of which was connected a cable undergoing test. The voltage wave is not unlike some of those shown in the papers. The current wave crosses the zero axis three times in a half cycle; its third harmonic has a greater amplitude than its fundamental. We have found the peak voltmeter very useful in checking such waves.

The instrument which we are using is based on the oscillograph principle, and therefore takes a very appreciable current, so we cannot use a condenser train as a multiplier without going to considerable trouble and expense. Therefore, we are obliged to use an instrument transformer to step down the voltage.

There has been raised some question regarding wave distortion taking place through a potential transformer. We have checked peak factors at various times with our peak voltmeter, but have never been able to detect any difference between those on the primary of the step-up transformer and those at the secondary of the potential transformer. As further, evidence, we have taken oscillograms of such waves.

In Fig. 2, the wave marked *G E* is the voltage wave of a special sine-wave alternator. As we have never been able to apply a load that would produce any appreciable change in the shape of this wave, we introduced an air-core choke-coil into the line in series with the primary of the step-up transformer. Due to the non-sinusoidal drop through this choke-coil, the voltage at the transformer terminals had the form shown by the Wave T_1. The wave T_2 was taken simultaneously on the secondary of the potential transformer. The oscillograph vibrators were connected so that both waves were on the same side of the zero axis, and the multipliers were so adjusted that each voltage wave had the same amplitude. It will be seen that there is no appreciable difference in the shape of the two waves. There is, of course, a slight shifting of phase through the two transformers. Any variation of the voltage wave form is due to the fact that the current produces *IR* and *IX* drops in the transformer windings, which differ considerably in wave form from that of the applied potential wave. Also these waves were taken at only 13,000 volts. I realize that, at the higher voltages, distortion may occur due to capacity effects in the transformer windings.

If Dr. Sharp has developed an instrument that will trap and hold transient voltage peaks so that their value may be determined, I am sure that it will be found very useful in connection with high-voltage testing, especially in cable testing, where there is a large amount of capacity in the circuit. We have evidence that surges occur very frequently when the cable is long and the voltage is high. I am certain that many cables have punctured at voltages much higher than have been shown on the indicating instruments, due to surges occurring in the circuit. The presence of these transient peaks may be wholly unknown to the person making the test, unless he has some such instrument as Dr. Sharp describes.

J. R. Craighead: I made a few experiments and got some data in connection with the use of the kenotron with the electrostatic voltmeter on high-tension circuits at 60 cycles. In order to get the matter down to a point where a comparison could be made with the oscillograph with series resistance, voltages were used, not of the order being talked about this afternoon, but with the maximum limited to 7000 volts. The oscillograph was used photographically each time, and measurements made as carefully as possible in order to determine the correspondence between the electrostatic and the oscillograph. The electrostatic itself was calibrated on a sine wave after each successive trial, in order to be sure that the instrument itself did not change. Three waves were used, the crest factors varying from 1.405, which was practically a sine wave, up to 1.56. One of the three waves, the one whose crest factor was 1.56 had three peaks between each pair of zeros, although two of the peaks were very small.

The results, of which I have made a tabulation, show that the maximum difference within six successive trials taken of the three waves, between the crest voltmeter and the oscillograph, was about 0.2 of 1 per cent. The maximum difference on any trial was about 1.2 per cent, which was practically as close as a standard electrostatic voltmeter of 10,000 volts could be used

PLATE V.
A. I. E. E.
VOL. XXXV, 1916

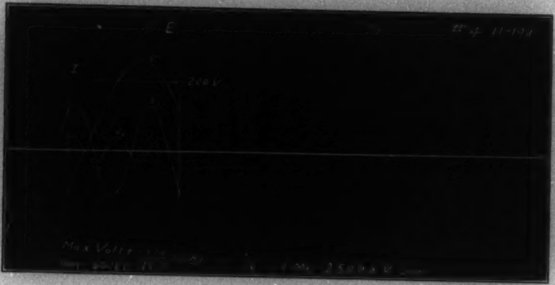

FIG. 1 [MIDDLETON]

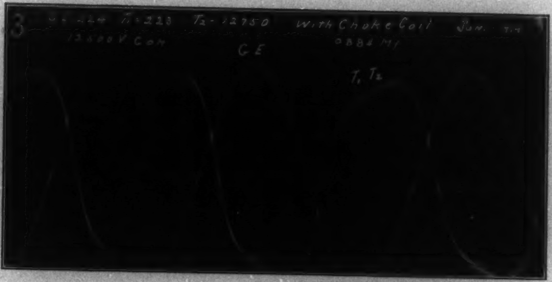

FIG. 2 [MIDDLETON]

at that point. All of the trials came within considerably less than 1.2 per cent, which represented the outside of the six.

In respect to the rectifier that was used, there is a characteristic of most rectifiers that causes them to have a rather definite voltage drop which is not altogether dependent on the current nor proportional to the current. In order to show as much of this drop as possible a kenotron was used which was capable of standing about 70,000 volts maximum, at about 10 per cent of the voltage it was expected to stand.

In respect to the capacity which was necessary in order to keep the voltmeter at a correct maximum reading, a very much smaller value than Dr. Sharp has suggested was found quite satisfactory. For the most part, these tests were made with 0.002 of a microfarad in multiple with the voltmeter itself.

The table to which I refer is as follows:

No. of test	Average crest factor	Average of maximum readings		Per cent variation of electrostatic voltmeter with Kenotron from oscillograph		
		Oscillograph through resistance	El. voltmeter with kenotron	Maximum positive	Maximum negative	Average
1–2	1.405	7186	7175	+ 0.7	− 1.0	− 0.2
3–4	1.485	7126	7185	+ 1.2	....	+ 0.8
5–6	1.56	7165	7165	+ 0.5	− 0.4	0

I ask Dr. Sharp if his tests were all made, as shown on the diagram, on ungrounded circuits or whether he used grounded circuits in any instance, and at what voltages the tests were made.

C. L. Dawes: There is still another type of crest voltmeter which has not been mentioned. We have found the oscillograph type of crest voltmeter very useful in connection with cable testing, but there are certain conditions under which it cannot be used to advantage because of the very appreciable current which it requires for its operation. This has led me to develop an electrostatic type of meter. The principle of the instrument is not original, but was suggested to Prof. A. A. Laws and myself by a paper written by E. T. Jones, appearing in the *Philosophical Magazine*[3] some time ago. However, the instrument there described was wholly unsuited for high-voltage testing, and therefore it was necessary to modify the design very materially.

Fig. 3 shows the general scheme of the voltmeter. For the sake of clearness, no attempt has been made to show the parts in their correct proportion. A phosphor-bronze filament is stretched between two points of support *AA*, the proper tension being secured by the spring *B*. This filament is held to the spring by a short length of silk thread for insulating reasons. Beside and close to this filament a small silk thread *C* is stretched, being drawn as tightly as its tensile strength will permit. Across the filament and thread, midway between the supports *A*, a small mirror *D* is cemented.

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[3] "A Short Period Electrometer and Its Use in Determining the Frequencies of Slow Electrical Oscillations." *Philosophical Magazine*, 1907, p. 238.

In front of the filament and very close to it, a brass plate *E* is fastened. Through the center of *E*, there is a small hole just large enough to allow a beam of light to enter and leave. The filament and this plate are connected together to form one terminal of the instrument. The other terminal of the instrument is the small brass plate *F*, secured to the hard rubber barrier.

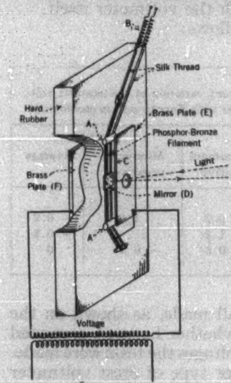
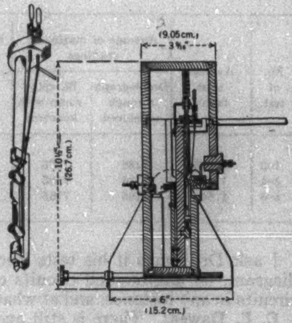


FIG. 3



FIGS. 4 AND 5

This barrier acts as a dielectric to prevent breakdown between the terminals.

When the brass plate *E* and the filament are both positive, there is electrostatic repulsion between them because like charges exist on both. On the other hand, there is attraction between the plate *F*, which now has a negative charge, and the filament. As the silk thread is not influenced by the electrostatic charges, it remains practically stationary, serving only as a hinge about which the mirror swings. Therefore, the left hand side of the mirror will be drawn toward the barrier. When the polarity is reversed, the mirror will still deflect the same way, because the charges on plate *E* and the filament are always the same and those on plate *F* and the filament are always opposite. Therefore, the mirror deflections are proportional to the square of the voltage and the deflection is always in the same direction. The deflection of the mirror is read by noting the breadth of a band of light upon a scale. Fig. 4 shows the vibrator which is removable from the barrier.

The instrument does not operate satisfactorily in air, due to corona and brush discharge from the filament, therefore it is necessary to immerse it in oil. Fig. 5 shows a cross-section of the instrument immersed in a box containing white oil. Connections to the plate are made through mercury cups, which connect to binding posts through hard rubber bushings.

It will be appreciated that this instrument has so little electrostatic capacity that it is almost negligible. Therefore, it is very easy to use it in connection with a condenser-train multiplier having a very small capacity. Also the instrument may be used to measure induced potentials upon insulated bodies whose capacity to the system is so small that the voltage would be disturbed by even the small capacity of other types of electrostatic instruments. For instance, Mr. Middleton and I have frequently used the instrument to measure induced charges on cable sheaths and on insulated conductors having high-potential wires in their neighborhood. This instrument does not need to be grounded, but may operate at potentials far above that of the ground. For instance, we have used it to measure a potential of 30,000 volts when one terminal was at 30,000 volts and the other at 60,000 volts above ground potential. Up to the present we have calibrated the instrument by connecting it to the secondary of a step-up transformer which is delivering no load. Under these conditions, we know the voltage wave to be essentially sinusoidal. The instrument at present can be used safely up to 30,000 volts, but there is no apparent reason why it cannot be designed to operate at much higher potentials than this, provided that appreciable corona discharge from the filament to the oil is not allowed to occur.

This voltmeter is independent of wave form and negative loops; although it cannot register surges, it has been able to indicate the apparent peak of surges in the circuit to which it was connected.

John B. Whitehead: All three of these papers describe the use of the electric valve for measuring the maximum value of voltage. Reference is made to the work of Dr. Gordon and myself in which we measured corona voltages at frequencies higher than sixty cycles. We used the mercury electric valve for obtaining maximum values of voltage at the higher frequencies, in much the same way as now described in these papers.

I mention this in order to answer Mr. Creighton's question as to the frequency at which the valves may be used. At that time we were working up to 3000 cycles. From the nature of the kenotron, I see no reason why it should not be available for far higher frequencies than this.

I wish to describe some experiments we have been making with still another type of crest voltmeter, namely, the corona voltmeter.

It has been frequently brought to the attention of the Institute that the value of the voltage at which the corona comes out on clean wires is extremely sharply marked. Suitable corrections, which are now perfectly well understood for temperature and pressure, may be made. It is quite possible to read and re-read corona voltages on clean wires to a far higher degree of accuracy than the constancy of the usual circuit, even in a laboratory, where precautions to secure constancy are taken.

Within the last two years I have been trying to use the principle of the breaking out of corona on the peak of the voltage wave as a basis for direct observation of crest voltages. The great difficulty in using the corona, a difficulty which is at once obvious, is that it is directly dependent upon the size of the wire, and that consequently for any range of scale in such an instrument the size of the wire would have to be changed. There is another difficulty, namely, that some method of detecting the beginning of corona, other than by direct visual observation must be devised.

I have met the first difficulty very satisfactorily, so far, by enclosing the whole corona tube, with its central wire, in a larger outside tube, varying the pressure in this outer tube and, reading the pressure and the temperature in order to apply the correction. The instrument can then be set for any voltage by varying the pressure in the outer containing cylinder, or, if it is desired to measure an unknown voltage, it is simply a matter of lowering the pressure until corona appears. In other words the range of the instrument will be taken care of by running the pressure either up or down in the outer containing tube.

For the observation of the beginning or presence of corona, we have developed three very satisfactory methods. The first is that which uses the gold-leaf electroscope in connection with a small electrode outside of the cylinder forming one side of the voltage terminal, as described in my papers, the *Electric Strength of Air*. This electrode is placed directly opposite a few small holes in this cylinder and the ionization that comes from these holes is quite sufficient to discharge even a crude and rugged type of electroscope.

The second method is by the use of the galvanometer in connection with d-c. voltage. In order to use this method, the electrode is increased in size, so as to form still a third outside cylinder very close to the main cylinder forming one side of the high-voltage circuit, the latter cylinder being perforated with many holes over its whole circumference so as to provide a very large aggregate opening for ionization. With d-c. voltage on the enlarged electrode and a galvanometer in series, the beginning of corona is marked by a sudden deflection.

Still a third method which has been surprisingly satisfactory is the use of the telephone. We enclose a telephone transmitter inside of the pressure cylinder. We do not normally think of a frequency of 60 cycles as one which would give any appreciable note with a telephone transmitter. There is, however, something other than the normal 60-cycle note in the high voltage corona and it is these higher spark tones which the telephone seems to pick out. The beginning of corona is attended by a sharp sound in a receiver connected to the transmitter located as described. We are now using all three of these methods of observation and they show a most gratifying agreement.

We can add a fourth method, if we will, the visual corona, always a very satisfactory means of observing the maximum point, but not suitable for an instrument for use in the open, as in a manufacturing shop, or power station. The eyes must be rested in the dark at least five or ten minutes before visual corona can be observed satisfactorily.

L. W. Chubb: In the paper by Sharp and Doyle the authors speak of leakage demanding a certain amount of capacitance in parallel to the meter. The dielectric resistance of electrostatic voltmeters is usually very much higher than any condenser, unless it be of the air type. Also, the rectifier resistance is higher in the reverse direction than that of the condenser, so that if more condensance is put in parallel we should expect more rapid discharge in spite of having more power stored.

Very likely the leakage between peaks is due to corona.

One of the speakers stated that he used less condensance when working at 7000 volts. Is it not likely that this was possible because the voltage was below the corona point and leakage was low.

Dr. Sharp speaks of registering the magnitude of surges with such an instrument, but I believe he will only reach a middle ground in obtaining a surge. The authors state in the paper that "if it does not build up on the first cycle it will on succeeding cycles." Sometimes the surges which come along are very steep, high frequency, and very quickly damped, so that if the first impulse is not enough to charge the electrostatic voltmeter and condenser, the following impulses will not be enough to raise the charge to the voltage of the first impulse.

The current through the condenser at the instant of a surge should be of the order of amperes instead of milliamperes. The kenotron current is limited by space charge and by temperature of the filament, so the condenser cannot be filled on the first impulse. Also with any appreciable damping constant, the succeeding peaks of the surge will not charge the condenser to the voltage of the first peak.

The multiplier method with two or more condensers in series with the electrostatic voltmeter in parallel with one unit would not divide the voltage by ratio during the surge transient, even if there were no current limitation of the kenotron, for if the voltmeter is to store a charge there must be an equal charge displaced in the opposite direction in the series condenser because a d-c. component of current cannot flow through the series condensers.

The ratio of series condensers has also been found to be wrong unless the several units are guarded by the principles which Mr. Fortescue presented before the Institute some time ago, and unless corona is prevented on any but the outside terminal of the end condenser.

The resistance multiplier is also open to the same objection and errors will result unless capacity to ground and between sections is eliminated by electrostatic shielding.

With the kenotron used on the high-tension side of the transformer as shown by the authors, it must be capable of standing twice the peak voltage, for on the reversed half cycle the charge of the condenser and the transformer voltage are in series adding. It therefore seems that the scheme, measuring crest voltage, would not be very simple on voltages above 100 or 200 kv.

I was very much interested in the test results given in Prof. Work's paper, and I may add I have seen very much worse distortions in testing waves which, I think, will give greater errors with a volt coil. We have tested out the voltage per turn through the secondary winding under various load conditions. In one case I remember the voltage in a secondary turn was reversed in a certain part of the leg from what it was in others. This means that if the volt coil is to be accurate it must be perfectly coupled with the secondary, or must be placed in the average position. The average position depends on the nature of the load, because there is a shift of leakage reactance between the two coils.

Our experience with the volt coil has not been very satisfactory due to improper placing and the resonance of upper harmonics between the load and the leakage reactance of the secondary. However, the results shown by Prof. Work indicate that the volt coil is quite reliable, when crest factor corrections are made.

Clayton H. Sharp: I evidently did not make it clear that these experiments were all made on low voltage, that is to say, the instrument itself, the electrostatic voltmeter, was graduated to read a maximum of 250 volts. So questions of huge condensers etc. do not apply to these experiments. The crest voltmeter as we worked it out was used on voltmeter coils, tertiary winding of the transformer, and one side of it was grounded, so that the whole thing was practically at earth potential.

There is no reason why it cannot be used on a condenser multiplier, and I do not quite see why the multiplier needs to be a whole string of condensers. It can be one high-voltage condenser, and in series with it another one of large capacity connected to earth. Thus one condenser takes the bulk of the voltage drop, and the other one, of larger capacity, takes a small portion of the voltage drop and the crest voltmeter is looped about that. Then the indications of the crest voltmeter will depend on the ratio of the two. While I cannot speak from actual experience, I do not see any reason why it should not work, and I do not see any reason why Mr. Chubb's condenser bushing could not be used as the high-voltage condenser.

With regard to the measurement of high-frequency surges, etc., what we have in our paper is simply offered as a suggestion, and is not backed up with any very positive statements, because we have not the data or the experience on which to rest them. In our paper we say: "In conclusion, it may be noted that the arrangement given offers possibilities in the matter of the study of surges." It may do it, or it may not do it. It looks to me as if, while it is rather improbable, that the full value of the first peak of the high-frequency surge would be given, at the same time the arrangement might be of a good deal of value, even if it did not give the whole thing. Undoubtedly, with a surge there would not be the same building up effect that there is with a steady alternating-current, because the first peak is the one that counts, the oscillations being damped out rapidly after that.

It will be noted, however, that if one kenotron has not a large enough saturation current to catch the surges perhaps two or three or more in parallel may have.

When commercial instruments are available by which the crest values of waves can be measured as readily as the effective values now are, we shall avoid a lot of trouble, escape a lot of mysterious things which occur in high-voltage testing and increase the accuracy and the worth of such work.

C. F. Harding: One very important feature of high-voltage measurement which has not been touched upon in the foregoing papers is the establishment of a more satisfactory primary standard than the combined needle and sphere spark gaps. That these are not entirely satisfactory is freely admitted, for they are subject to correction for barometric changes and in practise it is found very difficult to make the two standards coincide within the range between 30 kv. and 50 kv. where both are standard. Tests covering a large voltage range such as is required upon a line of pin type insulators or upon varying numbers of suspension units in a string are difficult to make when a double standard involving variable and uncontrollable factors is used.

Whereas the meters described in these papers are designed and intended for intermediate or secondary standard use and must be referred to the needle and sphere gaps for calibration, it may be of interest to reconsider the principle of the electrostatic field with a view toward its use as a high-voltage standard.

If, for example, a uniform electrostatic field can be maintained at the center of two horizontal circular metal plates of a relatively great diameter as compared with their distance apart, and if a small circular disc be cut from the center of the lower plate and supported upon a float just below the plane of the lower plate in a tank of liquid, the force required to raise this disc to the level of the lower plate can be readily calculated in terms of the voltage impressed between the plates. With the plates near together this voltage may be small and therefore accurately determined by other means than the spark gap. If

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the field is maintained uniform by applying higher voltages between the plates as they are separated from one another, the force necessary to hold the movable disc in the plane of the lower plate will be constant and the voltage will be directly proportional to the distance between plates.

Such an electrostatic voltmeter has been constructed at Purdue University by Messrs. B. S. Wright and H. R. Holman under the direction of the writer, and readings at low voltages confirm the theoretical straight line relation between voltage and distance between plates. This line extended may be used within the limits in which no corona forms for a standard of voltage, the particular instrument constructed having a range of 180 kv.

It should be noted that such a meter would indicate effective volts and that the crest voltage would be determined only after the wave form was known. However, since the crest voltmeters are equally restricted in determining effective voltages and since the latter values at high potentials are becoming of more importance as the losses in dielectrics are being studied quite as much as break-down voltages, further steps are being made to perfect the details of this instrument with the hope that it may be seriously considered in the future as a standard for high-voltage measurement.

W. D. Peaslee: Referring to Fig. 1 of Mr. Chubb's paper it must be recognized that the arrangement as shown will give satisfactory indications only on steadily maintained voltage conditions, as the instrument intrinsically gives a deflection that is some function of the entire wave or series of waves and will indicate an entirely unknown function on a portion of a surge which lasts in terms of cycles rather than seconds. For this reason the indication of the instrument is a measure of maximum voltage only when it is calibrated and used on a particular wave form. What is needed is an instrument that will indicate the maximum voltage applied regardless of wave form and even when this maximum is a combination of a normal frequency (60-cycle) voltage and a superposed high-frequency wave or transient.

It has been shown[4] that the voltage stress imposed on a system by the combination of audio and radio-frequency voltages is substantially the sum of the individual stresses imposed by the individual voltages.

It is therefor necessary in high-voltage testing that an instrument be developed that will indicate at the moment of failure, the actual maximum stress on the medium under test whether consisting of a steady 60-cycle voltage, a transient or a combination of the two. The sphere gap, as has been shown by Prof. Ryan and Mr. Peek gives a fairly reliable measure of the stress resulting from any of these combinations but it is in difficulty of manipulation that this device fails in most cases rather than in a failure to give on break-down an accurate indication of the maximum stress, as intimated by the author.

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[4] Sustained Radio Frequency High-Voltage Discharges" by Harris J. Ryan and Roland G. Marx, *Proceedings of the Institute of Radio Engineers,* presented Sept. 16th, 1915 at San Francisco.

The only device that seems at present to show distinct promise in this line is the cathode-ray cyclograph which, when properly handled will meet to a remarkable degree the requirements mentioned. The indications of this instrument are of maximum values and the calibration is easy. The duration of a surge measurable by it is dependent on the ability of the eye to catch the lengthening of the voltage line and it is hoped to develop a means whereby the eye may be replaced by an electric or chemical device and thus greatly shorten this interval.

As an indication of the extent to which this superposition of normal and high-frequency voltages may affect the results indicated by an instrument of the type described by the author we have found it possible, in the high-tension laboratory to subject an insulator to a stress just under flashover at 60 cycles and hold this stress on it indefinitely without puncturing the insulator. However, when besides this voltage at normal frequency we subject the insulator to a high-frequency stress consisting of several trains of damped high-frequency waves resulting from an arcing ground on the artificial line to which the insulator is connected it will be punctured with a very few applications, if the high-frequency stress is great enough. The instrument described in Mr. Chubb's paper will not give a reading that is a known function of the actual stress that punctured the insulator, but would indicate a lower maximum voltage than that under which the insulator actually failed.

Also the error mentioned in the discussion of Fig. 5 in the paper is a double one as the meter will not only integrate all the positive current areas and neglect the negative ones but will in the next half cycle, which should be entirely eliminated, integrate these negative areas. Thus the meter will read high by twice these negative areas. It will also be in serious error when applied to a wave consisting of a normal frequency wave with the superposition of high-frequency trains or surges.

Referring now to the paper by Messrs. Sharp and Doyle it is very probable that the charge will require several succeeding half waves. Also the fact that the instrument will not recede from it's maximum reading for an appreciable time after the application of the maximum, this time depending on the leakage of the equipment, may introduce serious errors in determinations made with this instrument. Suppose a test is required of 60,000 volts for one minute and that on bringing the voltage up the first few cycles, enough to complete the charge, this voltage was 60,000 but that it then dropped to 50,000 volts. The instrument, until leakage had permitted it to drop back to the lower voltage, would indicate that the required voltage was applied to the insulator while in reality it was subjected to 60,000 volts for a few cycles only and for the rest of the minute to only 50,000 volts. This might result in the acceptance of defective material.

This effect will be more serious the quicker the charge is built up and the less the leakage.

Also the use of the instrument as a surge trap is open to question until it is shown that the charge is built up in the time of the surge duration.

While these two papers are very valuable additions to the field of high-voltage testing and investigation, it would hardly seem that there was sufficient proof of the value and reliability of either method to accord them a place in the Standardization Rules at present, because of their inherent limits and also because it is quite probable that the cathode ray tube will be developed into a practical form for measuring these maximum values of voltage, both of normal frequency and transient wave trains, and of the two combined. As at present available it is much more satisfactory as a maximum-voltage measuring device than either of the instruments described and its failure on transients is due only to the inability of the eye to catch the record of the transient. If any change is made in the Standardization Rules the cathode ray tube should be carefully considered and given its rightful place as a means of measuring maximum-voltage values.

L. W. Chubb: Mr. Peek spoke of the errors due to corona. With the single condenser in series with the crest voltmeter there would be no error from corona, because you are measuring the voltage which is impressed upon the condenser. It does not matter how much corona there is, the line will supply all. If there are several condensers in series, the corona on and charging current of intermediate steps will cause an error except with the condenser terminal or with other similiarly guarded scheme. Each layer of the terminal is in its proper equal-potential surface, and there can be no corona, except possibly around the hat. These terminals will run to very high voltage without any corona at all, on the intermediate steps.

Mr. Peek spoke of the cost of such crest voltmeters going up as the voltage increases. I might add, with reference to the crest voltmeter described in my paper, that the cost goes down as the voltage increases. The condenser terminal is either a feature of the transformer, or it may be a roof bushing. As the voltage goes up, there is more current through the same condenser, and it takes less sensitive and cheaper instruments to measure it.

Mr. Farmer asked about the variation of capacitance of the condenser terminal. That is covered in the paper. It increased from 4 to 5 per cent from very low voltage up to 25 per cent over voltage, but this causes no error, as the crest voltmeter is calibrated in parallel with the spark gap and the variation is, taken care of in the calibration.

M. G. Newman: In the third paragraph of Mr. Hendrick's paper the statement is made: "For precise results at all loads and power factors, it is necessary and sufficient that the ratio of the flux linkages of the voltmeter coil and the high-voltage winding be a constant." This is done by the proper design and placement of the voltmeter coil. I would like to explain the method of determining the accuracy with which the above condition is realized.

Referring to Fig. 6, transformer (*A*) is the transformer with voltmeter coil under test. Transformer (*B*) may be a potential transformer or any transformer which can be used to step-down to a secondary voltage which can be easily measured.

Voltmeter (1) is connected to the voltmeter coil of the transformer (*A*) and voltmeter (2) is connected to the secondary of transformer (*B*). Excitation is applied to the low voltage winding of the transformer (*A*). First a reading is taken at no load, voltmeter (1) and voltmeter (2) being read. Various loads are applied at (*C*) (either capacitance or inductance), the voltage and frequency being maintained constant and readings being taken on both voltmeters. The accuracy of the voltmeter coil is good if the ratio of the voltmeter (1) reading to voltmeter (2) reading remains constant from no load to full load.

We do not have to depend upon the accuracy of ratio of transformer (*B*). The assumption is that the ratio of this transformer will remain constant while tests are being made.

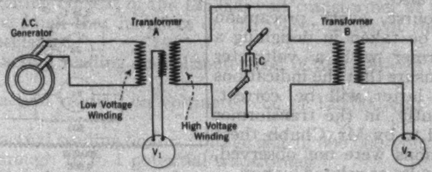

Fig. 6—Method of Testing the Accuracy of Voltmeter Coil

Errors due to flux leakage between the voltmeter coil and the high-voltage coil are shown to be very small.

A full capacitance load makes a small error in one direction and an inductance load an error in the other direction but with correct design these errors can be kept well below one per cent.

A. B. Hendricks, Jr.: I heartily agree with Mr. Peek in his final conclusion that "the voltmeter coil with crest voltmeter and supplemented by a sphere gap to detect oscillations offers the best arrangement for general commercial testing."

A crest voltmeter designed on the principle recommended by Sharp and Doyle, and connected to a voltmeter coil, has been constructed by Mr. Newman, and found to be in every way most satisfactory.

As it is built for low voltages and connected direct to the voltmeter coil, all parts are small, simple and inexpensive. In practise, the indications have been found to be correct and reliable.

Of course, this gives the crest value of periodic waves only, and does not indicate single transients of short duration.

As stated by Mr. Peek, the voltmeter coil reproduces the wave form in the high tension winding with such fidelity that there is no necessity for connecting static voltmeters or rectifiers directly in the high tension circuit, which is fortunate, since instruments designed for the extreme voltages contemplated have usually been unsatisfactory.

The method of using rectifiers, a condenser and a direct current voltmeter as described by Mr. Chubb is more complicated and less accurate on distorted waves of certain classes than the scheme described by Sharp and Doyle. It is not correct on multiple peaked waves, and the accuracy of the indications is absolutely dependent on the frequency. Neither of these objections applies to the scheme described by Sharp and Doyle, which is in other respects much simpler also.

Of course, every precaution should be taken in designing a transformer with a voltmeter coil to insure that the indications of the latter will be correct. Apparently, in the transformer referred to by Mr. Chubb, these precautions were not observed, with results as related by him.

As it seems to be difficult to convince the average engineer that the voltmeter coil is practically exact at all loads and power factors, I give herewith the results of tests recently made on a 300-kw., 300,000-volt transformer having one end of the high-tension winding permanently grounded. See Fig. 7.

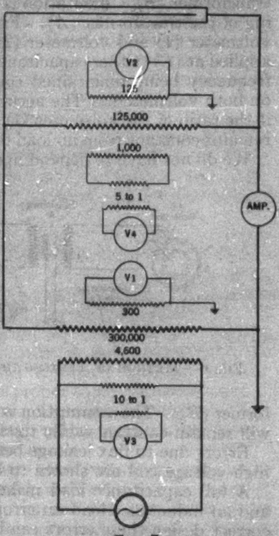

Fig. 7

The transformer was connected to a sine wave generator and the load consisted of a lead covered cable, especially made for use as a condenser.

The potential transformer consisted of another testing transformer rated 25 kw., 125,000 volts with one end of the high tension winding also permanently grounded.

With a pure condenser load it was found that the error of the voltmeter coil was too small to be detected by the best grade of portable dynamometer voltmeters, especially calibrated and interchanged, and read to 1/5 of 1 per cent.

This may be considered a zero error, since it is indeterminate by the most accurate form of commercial instrument, and even the sign of the error is unknown. At the same time the error, reading from the low-tension winding through a potential transformer was 7.6 per cent or close to the measured reactance voltage of the transformer, as was expected.

Normal rating of testing transformer:
60 cycles, 300 kw., 300,000 to 4600 volts.
Voltmeter coil reads 300 at 300,000 volts.
Normal rating of main potential transformer:
60 cycles, 25 kw., 125,000 to 1000 volts.
Voltmeter coil reads 125 at 125,000 volts.

Ordinary potential transformers of 10 to 1 and 5 to 1 ratio were used on the low voltage side of the 300,000-volt and 125,000-volt transformers.

Test was made at 60,000 volts and 0.88 amps. in the high-tension circuit, the normal rating being 300,000 volts, 1 ampere.

The *absolute* variation of high-tension voltage from the winding ratio depends entirely on the magnitude and phase of the current and the *per cent* variation at 60,000 volts is of course five times normal.

The exciting current of the 125,000-volt transformer at 60,000 volts is so small that its effect on the power factor of the load can be neglected.

V_1 = actual reading on voltmeter coil of 300,000-volt transformer.

V_2 = actual reading on voltmeter coil of 125,000-volt transformer.

V_3 = actual reading on low voltage side of 300,000-volt transformer through 10 to 1 potential transformer.

V_4 = actual reading on low voltage side of 125,000-volt transformer through 5 to 1 potential transformer.

Amperes = actual reading on ammeter in 300,000-volt circuit
= condenser + step down transformer currents.

The normal rated voltage of each winding is given on the diagram of connections.

The readings given are from the actual indications of each instrument after correction in accordance with the special calibration of each.

After taking one set of readings, the voltmeters were interchanged as indicated, and a second set taken.

Normal voltage..........	300	125	4600	1000
	V_1	V_2	V_3	V_4
Reading at 0.882 amps....	60	59.9	57.16	96.3
	V_1 & V_2 interchanged		V_3 & V_4 interchanged.	
Reading at 0.879 amp...	60	60	57.16	96.3

These readings were repeated and checked many times, with no appreciable difference in results. All taps on the voltmeter coil gave similar results.

One volt corresponds to two divisions on scale, one-tenth division being the extreme limit of observation, and probably beyond the accuracy of the instrument, or observer.

The voltages from transformation ratios of low voltage windings and potential transformer are as follows:

V_3 = 37,300 volts
V_4 = 60,200 "

The high voltage as determined by all the readings is therefore:

V_1..........60,000
V_2..........59,900—60,000
V_3..........37,300
V_4..........60,200

Voltage was fairly steady, but as each observer had to read two instruments, the observations are hardly reliable to 0.1 volt. Other readings of V_4 gave 60,075 volts.

The greatest care was taken in reading V_1 and V_2 on the voltmeter coils, the low-tension voltage being of less interest. The small potential transformers may also have slight errors. The voltmeter coil in the 125,000-volt transformer should be perfectly correct, since operation is at half voltage and no load. It is thus seen that the error in the voltmeter coil of the 300,000-volt transformer is zero or so small as to be indeterminate by any ordinary methods, and therefore negligible.

On the other hand, the rise in voltage due to the capacity load is from 37,300 volts (measured on low voltage terminals) to 60,000 volts or 60.9 per cent (22,700 volts absolute).

These results show that the voltmeter coil is certainly accurate within 1/10 per cent, and probably much less on full load, normal voltage and zero power factor leading. It would undoubtedly be equally good on lagging load, but this is never encountered in practise.

Similar tests were made at no load. The following results represent the largest apparent error:

	V_1	V_2	V_3	V_4
Reading at 0 amperes....	59.9	59.8	91.6	95.8

High voltage from above

V_1 = 59,900
V_2 = 59,800
V_3 = 59,800
V_4 = 59,870

From all the readings taken the average error *seems* to be about + 50 volts at 300,000 volts *at both normal and zero load*. This could be produced by an excess of two turns in the high voltage winding of 12,000 turns, or represented by one-tenth of a division on the voltmeter scale.

As a conclusion from all the results it is claimed that the error is less than ordinary minimum errors of observation and instruments, and less than those inherent in any other known method of measuring high voltage.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 9, 1916.

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OPERATION ON THE NORFOLK & WESTERN RAILWAY

BY F. E. WYNNE

ABSTRACT OF PAPER

This paper describes the great advantages, from an operating standpoint, incident to the inauguration of electric service on the Elkhorn grade of the Norfolk & Western Railway Co. and why it is possible almost to double the capacity of the road by the use of 12 electric locomotives, instead of the 33 Mallet locomotives formerly in service.

THE ELECTRIFIED portion of the Norfolk & Western Railway lies chiefly in southern West Virginia between Bluefield and Vivian, as shown in the map, Fig. 1.The distance by rail is 30 miles (48.2 km.) but, "as the crow flies," Vivianis only 18 miles (28.91 km.) from Bluefield. The approximate profile in condensed form is shown in Fig. 2. Curves from 8 deg. to 12 deg. are of common occurrence and the average curvature is over 3 deg. The maximum grades eastbound are 2 per cent against 2.36 per cent with the load. For westbound trains the maximum grades are 1.1 per cent against and 2 per cent with the load. These figures indicate the severity of the service so far as alignment and grades are concerned. With the exception of Elkhorn Tunnel, the entire line is double-tracked, with considerable third track, numerous spurs and cross-overs and several yards. At the summit of the long grade up the west slope is a 3000-ft. (914-m.) single-track tunnel, part of which is on a 3-deg. curve. On the east slope, just west of Bluestone Junction, is a 700-ft. (213-m.) tunnel over the westbound track only.

The principal tonnage is coal, a portion of which comes from points west of Vivian. Between Vivian and Coaldale, the adjacent hills are honeycombed with coal mines which furnish tonnage both east and west. In addition, coal from branch lines is brought to the electric zone at Eckman, North Fork, Lick Branch, Cooper, Bluestone Junction and Graham. Of course, time freight and passenger trains also pass over the electric zone. The gathering of tonnage trains of eastbound coal throughout the field is naturally accompanied by the delivery of empty cars from westbound trains to the numerous mines. Between Vivian and Coaldale, the line is operated as an elongated yard without intermediate telegraph stations. Communication with the load dispatcher may be had by telephone at each westbound signal bridge.

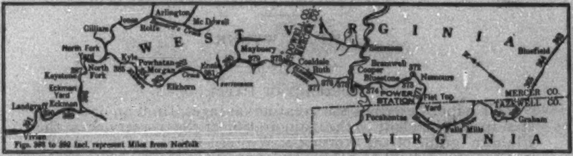

Arlington
McDowell
Jones
Rolfe
Gilliam
W E S T V I R G I N I A
North Fork Yard
North Fork
Keystone
Kyle
Powhatan
Morgan
Elkhorn
Ennis
Maybeury
Coaldale
Ruth
Eckman Yard
Eckman
Landgraff
Vivian
Simmons
Bramwell
Cooper
Bluestone
Nemours
POWER STATION
Flat Top Yard
Pocahontas
Falls Mills
Bluefield
MERCER CO.
TAZEWELL CO.
Graham
V I R G I N I A
Figs. 365 to 392 incl. represent Miles from Norfolk

FIG. 1

The foregoing conditions apply with both steam and electric operation. In order fully to appreciate what electrification is accomplishing on the Norfolk & Western Railway, it is necessary to consider other general conditions which differ under steam and electric operation.

Until 1911, comparatively little coal was hauled west over the hill. Eastbound coal constituted a decided majority of the total traffic. This was handled up Elkhorn Hill in 2360-ton trains with a Mallet locomotive, having eight driving axles, at the head end, a consolidation helper engine at the rear, and a consolidation pusher. Ordinarily the pusher locomotive did not work in the tunnel but remained with the train for emergency use. At Ruth, the east end of the long tunnel, the pusher cut off and returned west light or assisting in delivering empties on the west

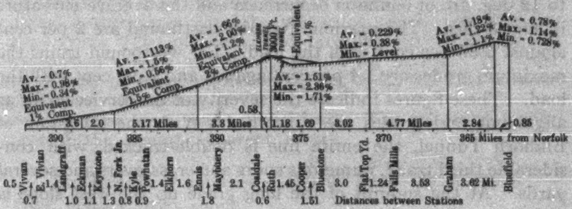
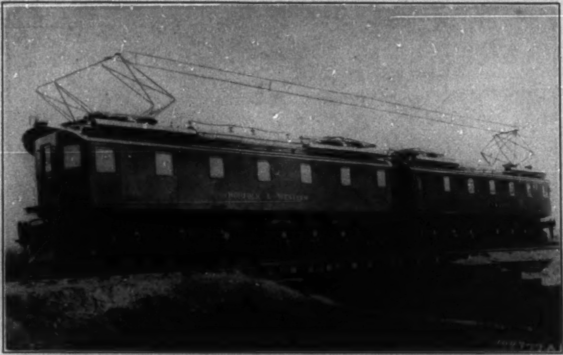
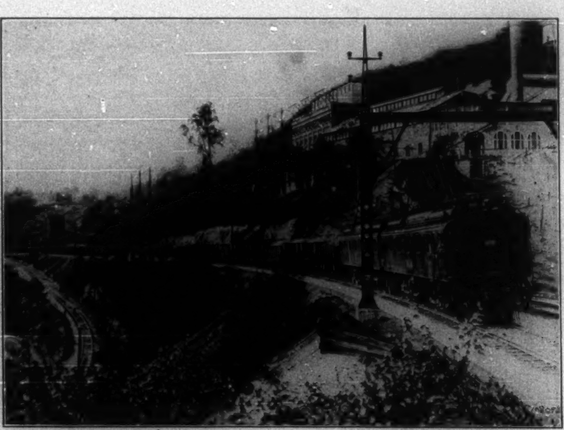


FIG. 2



[WYNNE]

FIG. 3—270-TON ELECTRIC LOCOMOTIVE USED ON NORFOLK AND WESTERN R.R.



[WYNNE]

FIG. 4—ELECTRIC LOCOMOTIVE AND COAL TRAIN ASCENDING GRADE AT SWITCHBACK

slope. From Ruth to Bluefield, the train was handled by the Mallet and helper. On this part of the run, the helper was necessary only for assisting the train up Graham Hill. This assistance might have been given by a pusher operating between Graham and Bluefield only, but for the fact that the helper was required for delivering westbound empties and it was impracticable to hold locomotives for this purpose at Ruth or Coaldale between the time of helping an eastbound train up Elkhorn Hill and the time a westbound train of empties arrived.

Westbound, the Mallet and helper ran light or with a train of empties (sometimes amounting to 125 cars) and occasionally picked up at Flat Top a small number of westbound loads. Practically all of the switching, picking up loads and setting off empties was done by the consolidation engines. As much of the tonnage originated along Elkhorn Hill, some trains started with less than the rated tonnage and filled out at one or more points. When this was necessary and also when delivering empties, the train was held by the Mallet at its head. On rare occasions, the Mallet helped in filling out the train.

A number of difficulties were experienced with steam operation. In starting on the hills, the rear engines, with steam in the cylinders, held the train until the head engine got its portion of the train under way. This period of standing under load ran from 30 or 40 seconds up to two or three minutes and often was repeated a number of times before the train got started. As the locomotives were rated practically at their maximum tonnage with good rail, slipping was a frequent occurrence when any condition reduced the adhesion. The slipping of either consolidation or one truck of the Mallet caused a loss of one-fourth of the motive power on the train.

On the west slope, eastbound locomotives took coal and water at two points, one of which was at times the starting point. Another stop for water was made at Cooper or Flat Top. The delays due to this were in themselves considerable, since at each coal or water station either two or three engines had to be cut off from the train and handled separately, the train being pulled up in the interval between supplying the head and rear engines. The attendant delays due to congestion were even more serious. At times, three or four trains followed each other closely, resulting in a delay at coal and water stations of about two hours for the last train of the fleet. Frequently further delays were encountered, because by the time the third or fourth train was coaled and watered, it was necessary to clear the main line for one or more superior trains.

The low speed on grades with steam locomotives was another feature making operation difficult. On the heavy part of the grade from Ennis to Ruth the speed seldom exceeded six miles (9.6 km.) per hour and was often as low as four miles (6.4 km.) per hour. The fastest time freight was scheduled at only 9.5 miles (15.2 km.) per hour from Vivian to Coaldale and 13.3 (21.4 km.) miles per hour from Coaldale to Graham, while the fastest passenger train had a schedule of 19.5 miles (31.3 km.) per hour from North Fork to Coaldale.

The Elkhorn Tunnel was, to say the least, an unpleasant feature of steam operation, the grade being such as to require both the Mallet and helper to work through it going east. Although it was ventilated by fans blowing in the west end and the train speed was low, considerable smoke and gas were still in the tunnel when the helper and pusher went through. A little imagination can picture the conditions when a train stopped in the tunnel and all three engines had to work to start it.

Under the foregoing conditions, the maximum number of freight cars handled up Elkhorn Hill in one month was approximately 17,000. The average time of a round trip between Bluefield and the coal fields was 12 hours, and this constituted a day's work for the train crew.

Between 1911 and the time of electrification, additional Mallets with arches, superheaters and stokers were applied in this service and larger three-engine trains with Mallets in each position were operated. This afforded some relief, but 33 Mallets were required to handle the traffic in this way.

In 1911, no consideration was given to the electric operation of time freight and passenger trains. Now, in addition to handling coal trains and empties, the electric locomotives are pushing all eastbound time freights to Ruth and two of the heaviest eastbound passenger trains to Bluestone Junction.

One electric locomotive at the head and one electric pusher take trains of 3250 tons east to Ruth where the pusher cuts off and returns west light or assists in delivering empties. From Ruth to Flat Top, the head engine alone suffices. At Flat Top, the train is filled out to 4700 tons and an electric pusher is attached to assist the train to Bluefield. A regular day's work for a head crew is to take a train of empties from Bluefield to the west slope, return with loads to Flat Top, then run west light, with empties or with west loads to the coal fields and return with loads to Bluefield. An Elkhorn pusher crew frequently handles five or six eastbound trains as a day's work, while a Flat Top pusher at times exceeds this on account of the shorter distance. With the electric locomotives, gathering loads and delivering empties may be accomplished equally well by either the head or rear locomotive.

On account of the length of train and curvature of the track, it is at times impossible to hear whistle signals. In starting a train with two engines, other means of signaling are used. The head locomotive releases brakes and lets the slack run back. As soon as the engineman on the pusher feels the blow resulting from this, he applies power and holds the train until the head engineman has applied power and gotten the front portion of the train sufficiently under way to permit motion of the rear locomotive and its share of the load. The period of standstill with power on for the pusher engine with this method of operation rarely exceeds 30 seconds and generally a satisfactory start is secured on the first attempt. This speaks well for the smoothness of the electric control, as the electric locomotives have less weight on drivers per ton of trailing load handled than was the case with steam locomotives. When slipping does occur on one truck, the loss of motive power is only one eighth of the total or one half of the proportion which occurred with steam.

The delays for taking coal and water have been eliminated from the trains which are operated entirely with electric engines, and have been reduced on those trains which are only pushed electrically. Consequently, there is also a great reduction in the time lost in secondary delays which were formerly produced by coaling and watering.

By means of pole changing, the electric locomotives are arranged for two speeds. The 14-mile (22.5 km.) per hour speed is used regularly for the heavy freight work, while the higher speed of 28 miles (45 km.) per hour is used for passenger trains, light engine movements and a certain amount of time freight operation. As a result, the speed of the coal trains has been more than doubled on the heavy grades and the average running speed for eastbound loads over the entire trip from the coal fields to Bluefield has been increased over 50 per cent. In passenger service, it is a common occurrence to pick up a train 20 minutes late at North Fork and put it into Bluestone Junction on time.

The dangers of steam operation in Elkhorn Tunnel have practically been eliminated. The majority of the trains passing through this tunnel have only electric locomotives attached. Nearly all of those which do have steam engines on them are pushed through by the electrics at not less than 14 miles (22.5 km.) per hour with the steam locomotives doing very little work. How satisfactorily this is accomplished is indicated by the fact that in assisting time freights with a steam locomotive on each end, the head engine working and the rear engine idle, the electric pusher works through the tunnel with its windows open and without noticeable smoke or gas in the electric cab.

Certain features of the locomotives are notable in their effect on the handling of trains. The control is extremely flexible. Power may be applied to the motors of one truck on each half of the locomotive in starting. This is particularly advantageous with a light engine or a train of empty cars. In changing the speed, one half of the motors are changed at a time so that the entire tractive effort of one locomotive is never lost.

The arrangement for operating the rheostats is such that practically an infinite number of steps is provided for acceleration. The effect of unequal wheel diameters in unbalancing the loads on different motors may be readily counteracted. In case of wheels slipping, the load on the slipping drivers may be reduced until they again grip the rails, without reduction in the tractive effort developed at the drivers which are not slipping. In case of trouble, either a single truck or a half engine may be cut out without affecting the operation of the remainder of the locomotive.

The inherent regenerating feature is of great value in controlling the trains on down grades, and the fact that the speed down grade is constant and inflexible prevents the possibility of surges in the train which would result in broken draw-heads.

Considerable assistance in effecting a smooth stop is secured with trains having two locomotives approximately one-half mile apart by passing the load from locomotive to locomotive while backing off the control. To be a little more specific, when the head engineman desires to make a stop, he introduces a portion of the rheostat into the circuit of his motors. This slightly reduces the speed of the head engine and throws additional load on the rear locomotive. The latter, noticing the increase of load, realizes that a stop is about to be made and he too starts inserting resistance into his motor circuits, always, however, keeping his tractive effort up near the maximum. The front engineman, on the other hand, inserts his resistance more rapidly, reducing the speed of his engine at a slightly greater rate than the rear engineman and allowing the latter to "bunch" all the slack in the train. As soon as the slack has all been bunched, the head engineman shuts off and if necessary makes a slight reduction with his automatic brake to bring the train to a stop. The rear engineman in his turn introduces more and more resistance into his motor circuits to keep from overloading his motors, until flush level has been reached. When he gets to this point, he holds his resistance constant until the train has been brought to a dead stop. He then makes a 30-lb. or 40-lb. application with his independent brake and having done this, throws his master controller to the off position.

Since electrification, not only has the eastbound traffic been very heavy but the westbound traffic from Flat Top is comparatively great when referred to that of 1911. Complete operating data are not available for publication at this time. However, a few general figures derived from the performance since the first of June, 1915, will serve to indicate what electrification is accomplishing. Compared with the Mallet locomotive performance of 1911, the despatcher's reports show that the electric locomotives are making eight times as many miles per train-minute delay due to locomotive failures in service. They further show that the electric locomotives have handled up Elkhorn Hill in a single day 50 per cent more slow freight tonnage than was handled by steam locomotives in the maximum day recorded prior to the summer of 1911. This was done with only nine of the twelve electric engines in service. From Nov. 1st to Dec. 17th, inclusive, there was no delay due to failure of electric locomotives in service. During this period the electric locomotives made nearly 45,000 miles (72,420 km.) with approximately 700 freight trains and 25,000 freight cars, each of from 60,000 to 180,000 lb. (27,215 to 81,646 kg.) capacity, eastbound up Elkhorn Hill. In addition, they pushed an average of two passenger trains per day up the hill and cared for an unknown quantity of switching service and westbound freight traffic. Presumably, the railway company will at some time in the future give statistics showing, better than is now possible, the heavy traffic and severe service which electrification is successfully meeting in this installation.

DISCUSSION ON "OPERATION ON THE NORFOLK AND WESTERN RAILWAY" (WYNNE) NEW YORK, FEB. 9, 1916.

A. H. Armstrong: The induction motor has one inherent characteristic, constant speed at all loads, that makes it of doubtful application to the haulage of trains over a broken profile. The speed of the motor can be varied only slightly except by changing its number of poles, a matter of doubtful expediency in its practical application to the operation of a train. We have been educated in steam railroading to expect the flexible speed characteristic of the steam engine, that is, slow running on ruling grade and proportional higher speed on the lesser grades and level track. Railroad practise therefore is more or less crystalized about the flexible speed operation of the motive power, and in adapting the induction motor to train haulage we are going against all previous ideas, and the continued operation of the Norfolk & Western Railroad will be watched with considerable interest as throwing light upon the adaptability of the induction motor to main line service.

The author gives little data in regard to the question of change of speed except that certain lighter trains will change from 14 to 28 miles per hour where the ruling grade is favorable. No reference is made to the fact that drag freight trains operate over a broken profile, and the inference is gained that such trains operate at a constant speed even on the considerable stretch of low grade track over which a higher speed would be permissible. With the steam locomotive or the d-c. motor locomotive, the sloping characteristic curve inherent in such motive power automatically provides for a change in speed inversely proportional to the gradient of the track.

Very little is said in the paper about regenerative braking although the induction motor inherently provides this feature. So much interest is attaching to electric braking on the Chicago, Milwaukee & St. Paul installation that I may be justified in commenting upon several operating facts found in connection therewith. The method of handling trains going over the crest of the grade and starting down is a matter calling for a considerable amount of skill. Having little to guide us in this direction I had hoped that the author would have brought out something more of the practise prevailing on the Norfolk & Western.

As the train surmounts the grade and the leading locomotive starts to descend no trouble is experienced in applying the electric brakes and in passing from motoring into braking unless the train is brought to rest and then re-accelerated on down grade. In starting on a down grade it is sometimes difficult to change from motoring into braking without introducing the possiblity of breaking the train in two. One method of minimizing this trouble is to tip the retainers on a certain number of the leading cars of the train so that an application of air will result in bunching the slack on the leading locomotive.

The change from motoring to braking can then be effected without occasioning a surge. It has even been possible to hold back a 3000-ton train on a 2 per cent grade with electric locomotives in different parts of the train both braking electrically. No exact method of handling the train down grade has as yet been established, but the greatest success has attended the use of electric brakes and the energy returned to the line has been approximately 15 per cent of the total average demand of the first engine division electrified on the Chicago, Milwaukee & St. Paul road.

It is, of course, understood that retainers are kept in use only during the initial period of changing from motoring into braking, the air is then allowed to leak out and the train handled in its entirety by the electric brake. The electric brakes will hold back the entire train provided the locomotive weight on drivers will furnish the necessary tractive effort without exceeding a coefficient of adhesion permissible with the condition of the rails. For example, on ore roads where the grade favors the load it is current practise for the locomotive to handle a train down grade which is very much heavier than the same locomotive could haul up grade. This is made possible by the application of air brakes to all cars, and if an attempt is made to hold back the train by electric brakes on the locomotive it would demand such a high tractive effort as to exceed the ability of the locomotive to hold the train back and the wheels would slip. With such trains therefore it is necessary to supplement electric brakes by a certain amount of air brake application or else install locomotive capacity greatly in excess of what would be required to haul the empty cars up the grade on the return trip. The combined use of electric and air brakes introduces some new features which are not as yet reduced to a standard practise, but undoubtedly the constant speed characteristic of the induction motor introduces a handicap where electric braking is supplemented by air brakes, and this is due to the small latitude which such motors permit in speed variation. The d-c. locomotive is much more readily adapted to the combined use of electric and air brakes, as the speed at which electric brakes can be applied extends over a considerable range and thus fits in better with the combined use of electric and air brakes in cases where the electric locomotive has not sufficient weight on the drivers to hold back the trailing load on down grade. The constant speed characteristic of the induction motor therefore may prove to be a serious handicap not only during the period of motoring over a broken profile but also during the regenerative period down grade where the combined use of electric and air brakes may be enforced.

Some reference has been made to the question of wheel correction, that is, the induction motor being a constant speed motor will operate at a constant rotative speed while the locomotive speed will be proportional to the wheel diameter. When all wheels are new any two locomotives may be coupled together in the same train and all motors run at the same speed. After the tires have been turned, however, there might be coupled to the same train two locomotives having tires of different diameter, in which case a constant resistance must be interposed in the motor secondary geared to the larger wheel diameter in order that the wheel peripheral speed shall conform to that of the smaller wheel diameter. This constitutes a loss in efficiency which is peculiar only to the split-phase or induction motor type of locomotive and adds to the burden of locomotives of the Norfolk & Western type which already have a very low efficiency due to the losses in transformer, phase converter, gears, jack shaft, side rods, etc. It will be interesting to know the efficiency of these locomotives especially after they have been operated for a sufficient period to call for the turning of tires.

R. E. Hellmund: The regenerative control of the Norfolk and Western locomotives, was found to work much easier and better than had been anticipated. When the heavy train is pulled up the hill and passes the crest, it is only necessary to keep the power on the locomotive in the regular way and the locomotive picks up the regenerative load car by car automatically and the engineer has practically nothing to do. You can stand on the locomotive and watching the ammeters observe the increase in regenerative current as each car bumps up against the car in front of it; there is a succession of these little bumps, and you can practically count the cars as they are picked up by the locomotive. It works very smoothly and without any trouble. In fact, some of the operation which originally it was not contemplated to do by electric braking is now being done in this manner, because it is much easier than the air braking.

In the control of the locomotive, the water rheostat is of some interest, in so far as its control is different from the type of controller commonly used on electric locomotives. We are all accustomed to have a master controller which is worked by notches, to increase the voltage on the motors or change the connections. In this particular locomotive the water in the rheostat is lowered and raised by means of a handle, the operation of which is somewhat similar to the operation of the throttle lever of the steam locomotive, and it seems that the steam engineers find that very convenient and much to their liking

As to the limiting speeds of the induction motor, which have been considered so much of a disadvantage, we find more and more that this feature can hardly be considered as such. About six or seven years ago whenI first saw three-phase motors operating in Italy, I was very much worried about their disadvantages. I was told however, that as an actual fact, the service could be handled better and easier than with steam, and while steam trains were frequently late on the steam lines the electrical trains hardly ever were late; this is because variable speed locomotives will lose time with overloads, while the three-phase motor always runs at the same speed and there is less chance for losing time.

Then, of course, there is the possibility of losing time in the stations for various reasons, and the argument is that such time cannot be made up by the constant speed locomotives. It is to be considered in this connection that most railway equipments are worked about to their limit nowadays, and whether you have the series characteristic or the constant speed characteristic, you cannot make up time except by shortening the coasting period. This can be done with a three-phase motor as well as with a series characteristic motor. If you want to make up time, the only chance you have in either case is to make it up by keeping the power on longer. For this reason it seems that the slight difference between the two motor characteristics apparently does not grow to be a great disadvantage in actual practise. In Italy they handle passenger traffic to a very large extent with three-phase motors, and they are altogether satisfied with the limited speed characteristic.

Francis H. Shepard: Railroad service on the Norfolk and Western is far from toy railroading. These locomotives weigh 270 tons, and to give you an idea of the amount of power handled, with an ordinary train accelerating on the grade the power runs from 8000 to 9000 kw. per train. On certain accelerations which have been made for demonstration purposes, the power reached 12,000 kw., and on a single locomotive, also for demonstration purposes, on the 28-mile connection, 8000 kw.

In handling a long train, I might say that some twenty years ago I lost my respect for the strength of railroad equipment. Down in the Baltimore and Ohio tunnel we broke trains in two as though they were a string of egg-shells. A train is not an inflexible structure; the least little jerk on the controller may tear the train in portions, and one of the necessities in handling heavy trains, and particularly in getting satisfactory performance with the train, is to have absolute control of the motive power. The more refined control of the train you can get the better off you are.

It is a serious matter for a Mallet pusher to slip at the rear of a train, in that it commonly results in breaking the train into two or three parts. When you break a train in two on these grades with cars with lading which weigh 130 tons each, it is because no draw-bar or draft rigging can stand the surge and shock. For instance, on one occasion on the Norfolk and Western inadvertently the trolleys were lowered on the rear or pusher locomotive; the power was cut off thereby, and the train broke into three parts. These locomotives are, of course, interesting to everyone who sees them and rides on them. This accident happened because the conductor seeing these levers wanted to know their function and whether they were operative, and was told " No, they are all cut out, except on the operating end." That was the fact, except for the trolley down button. That was the very one he pushed.

The operation of the liquid rheostat has been amazingly successful. There are many operations which take place in handling these heavy trains which do not follow the pictures we ordinarily consider railroad operations are governed by, the speed-time curves of the designing engineers.

It is not uncommon for a train to have stuck brakes, to have an excess tonnage, or to require a slow-down movement, and the facility and capacity of the water rheostats to secure these abnormal operations is, as I have said, amazing. The curvature on the Norfolk and Western is so great that with the long trains it is quite impossible to pass the customary whistle and other signals from the head to the rear of the train. In the operation up the grade, the head engineer gets a " slow " order, the pusher engineer has no knowledge whatever of this, the head engineer shifts his load by inserting resistance, the rear engineer receives immediately a corresponding increment of load, he also in turn shifts, and thus they may drop down to half speed, or less than half speed, and then when the slow order has been satisfied and they wish to accelerate up to full speed again, the head engineer opens up; the rear engineer sees he is opening up, so he does likewise, and the whole operation is carried on without any surge to the train whatever.

The result of this is that extreme facility in operation is secured and a very material decrease in damage to equipment over that inherent to a variable speed locomotive such as one operated by steam.

As to the inflexibility of the induction motor, a few years ago I agreed entirely with Mr. Armstrong's opinion, as expressed this evening, but I must confess that I have changed, and that change in my position has been very largely governed by our operation and analysis, together with contact with railroad men. These motors operate so satisfactorily that the dispatchers and tower men will despatch one of these constant speed trains ahead of a passenger train, definitely figuring on only a minute or two leeway, and know that the train is going to clear. You thus get the capacity out of the railroad because the dispatchers and tower men know that trains will start and clear in a certain number of minutes and that the first-class trains will not be held up. In the case of steam operation, when they give a train a clear track they do not know when it is going to clear.

The operation of the induction motor for regeneration is exceedingly simple, and the ease with which it is operated has resulted in the men using the air brake only when they really have to, that is, to come to a standstill. Even in light train or single locomotive operations it is not unusual for them to regenerate, because it is the simple and easy way of governing the train.

Every one who has ridden on a mountain grade knows that the dropping of a train down a grade is not at constant speed or anywhere near constant speed. The train hunts in speed up and down the grade, and before you get the last service application to the brakes you are always more or less concerned, and greatly relieved when you know that you have reached the foot of the grade. In swinging over to constant speed regeneration, while going over the summit of the grade, the operation is simply the switching of the levers to secure a little better operating characteristic on the locomotive,—it is not really essential,—and we take down a train of 103 cars, which is a pretty sizable train without touching the air and would not spill a drop of water out of a glass in the caboose.

Swinging into regeneration from start, on a down grade can be accomplished with about the same facility. There was originally some concern as to how we would tip the train over the summit, whether the head engine would not give a terrific surge to the train, but as I say, this is handled with great smoothness.

In taking a train down a mountain grade with this system, you feel as though it were tied; that is, the sensation when you go down with a constant speed locomotive, no running up in speed and no occasion, therefore, for any excess in tractive effort above the holding tractive effort. There is a vast difference between the adhesion required to start a train on a grade and the adhesion required to hold that same train going down a grade. By that margin this inflexibile characteristic is advantageous.

We are taking 3250-ton trains down a pitch of 2.4 gradient from the head end without touching the air. This exceeds the adhesive limit you would ordinarily assume. This is done regularly, a dozen or twenty times a day. If, for any reason, the rail is bad, you can very readily touch up the train with a light brake application, and take part of the retarding effort with the train brake. I may say that retainers are not used, they have not been found necessary to secure smooth control of the retardation.

If the engineer should for any reason during regeneration handle the train brakes improperly—and, by the way, there is more opportunity to wreck a train by improperly handling the air-brakes than in almost any other way—the constant speed characteristic in the induction motor shows its great advantage, for the speed of the train is absolutely held until the train brakes have full control of the train. The train brakes must positively have control of the train before the locomotive holding that train loses its holding power, and therefore it is a perfectly safe and smooth operation, simply to shut off the controller.

In bringing the train to a stop on the grade, the brake application is always made first, and as soon as the motor ceases holding, the train is under full control by the air with auxiliaries fully charged, there is no chance of running up, and the train is slowed down from its constant speed of fourteen miles an hour.

The men who handle these constant speed motors are delighted with their inflexible speed characteristics and it is noteworthy that on regeneration there has never been a case of slid wheels or train broken in two.

B. A. Behrend: We have discussed the subject of the electrification of trunk lines for the past ten years. The situation seems to be about the same today as it was ten years ago in regard to unanimity of opinion as to the best system available. Mr. Wynne's paper and Mr. Shepard's able discussion of it have demonstrated without doubt that single-phase generation and single-phase distribution to single-phase-three-phase locomotives has been successfully executed on the Norfolk and Western Railway. Mr. Armstrong's discussion has reminded us that high-voltage d-c. distribution to high-voltage d-c. locomotives can be, and also has been, successfully carried out on a large scale. We are further aware that single-phase generation and distribution to single-phase locomotives has worked out successfully on the New Haven Railroad. It remains only to raise the point whether the difficulty of three-phase distribution is such as to make impossible the use of three-phase generation, three-phase distribution, and three-phase locomotives. Unless the use of two trolleys, which three-phase distribution necessitates, is as prohibitive as the railway engineers make us believe, it would not seem permissible to resort to the additional complications of adding on each locomotive a single-phase three-phase synchronous converter. It must always be borne in mind, as has frequently been stated since the advent of the single-phase railway, that the generation of single-phase currents is a very uneconomical process, involving problems of design of single-phase generators which are very difficult of satisfactory solution. It must always be borne in mind that the best single-phase generating plant conceivable, if it were to be utilized for three-phase generation, would, electrically, almost be doubled in capacity merely by the utterance of that magic word three-phase for single-phase. After all, then, perhaps, such great engineering achievements as the electrification of the Norfolk and Western Railway, or the Chicago, Milwaukee and St. Paul Railway, must be described as the least unsatisfactory solution of a difficult problem rather than as the most satisfactory solution that can be devised.

W. I. Slichter: Whether we believe in one system or the other, I think that all of the systems have shown that the electrical engineer by one system or another can move the freight and the passenger traffic on big trunk line railways more economically, more reliably and more satisfactorily than the steam locomotive. Each system, as Mr. Behrend has said, accomplishes the result, and whether it is the best system in the end, I believe nobody is able to say any more that any one can say any particular steam railway has the best system.

In this system we have the application of three-phase motors to heavy work. I think we all concede that this heavy coal-bearing traffic is the best place in which the three-phase motor could be put. The three-phase motor has the great advantage of being able to regenerate power with the simplest and easiest connections. It has the disadvantage that it is a constant speed motor, and that it is very sensitive to changes in voltage. That is one point on which I would like to question the author—what variation in voltage at the locomotive has been experienced in practise, and whether this loss in voltage has been found to be of any great disadvantage. We are aware that the torque of the induction motor decreases as the square of the voltage.

The phase converter is a very interesting piece of apparatus, which meets the railway operator's criticisms of the polyphase motor, in being able to take single-phase currents and convert them to three-phase currents and give the polyphase induction motor the currents it needs. At the same time, it adds one more link in the chain as to reliability and as to drop in voltage. It adds certain increase in weight, and we have then the question—Is it worth while?

This regeneration is of very great value in saving equipment by holding the trains on the curves, but it requires additional care in management. On this road is the traffic sufficiently great so that the regenerated energy from trains going down grade may be taken care of adequately by trains going up grade, or is some regulating device provided, so that in case trains are only going down grade and none going up grade, the excess energy will be absorbed somewhere?

R. E. Hellmund: The previous speaker made reference to the sensitiveness of the induction motor to voltage variations. It is quite true that the torque of the induction motor varies with the square of the voltage, but on the other hand it is not at all difficult with these large motors to design them for torques very much in excess of the rated torque. With the Norfolk and Western locomotives, for instance, I believe the slipping point of the wheels is about, I should say, 200 per cent of the rated load of the motors, while the motors are good for 400 per cent at normal voltage. Thus you can readily see that assuming 20 per cent voltage drop, or even 25 per cent, and a corresponding drop of 40 or 50 per cent in torque, the motor torque will still be in excess of the slipping point of the wheels, in other words, there is always plenty of torque to get started. After the motors are once up to speed, the variation of voltage simply means that the load current will change; it will increase inversely proportionate to the voltage; however, the increased copper losses caused thereby are largely compensated for by decreased core losses, and for that reason it is a matter of fact that the induction motor will run with pretty nearly the same temperature with voltage variations of 10 to 20 per cent. Of course, that depends somewhat on the detail design, but as a rule there is not much difficulty in taking care of the voltage variation.

Charles F. Scott: We have before us certain railway performances. In steam railway operation there is no performance equal to that which has been described here this morning. Trains of over 3000 tons have been run up grades at the rate of 14 miles an hour, train after train, in regular and heavy service. After the long development of steam locomotives, a dozen or so of the electric locomotives are doing the work of something like thirty of the best steam locomotives that could be obtained. The electric train service is something like twice what is possible with steam, *i.e.*, the highest speed and power found practicable in steam operation have been doubled in electrical operation and the capacity of a congested track has been doubled.

In comment, what are some of the questions which are asked? Some inspect the outfit with a sort of microscope and say, "This might be different, or that might be different." One of the gentlemen who took part in the discussion this morning, is artistically pessimistic. He says about the generator—"Why, if it were a three-phase generator, you could get twice as much out of it." Surely, but the generator is a small part of this system. Moreover, is not the generator on the basis of kilowatts output per pound of generator, giving a performance comparable to that of any generator, a dozen years ago?

A question has been raised about two trolley wires. Would it not be better to use them instead of putting in the phase converter? Is this not a simple matter of detail, a matter of compromise, between the mechanical objections to running the extra trolley, and the objections to putting a little more apparatus on the locomotive? It is really calling on the electrical system at the two ends to bear the brunt of the mechanical objections to the additional trolley. If the three phase system had been employed on the line as well as the locomotive there would have been required two overhead high-voltage contact wires instead of one; two current collecting devices on each locomotive instead of one; two oil switches instead of one; transformers for three phases instead of one; a three-phase motor for driving the blower and compresser instead of a phase converter which serves the double service of phase converter and motor.

It has been alleged that the induction motor does not permit a higher speed on level track; but in this particular case the change in the number of poles secures a speed of 28 miles, or double that employed on the grade. This is a higher speed than would ordinarily be obtained from a direct-current equipment.

True, electrical engineers do not agree among themselves, on all plans and details. But, our variations are no wider than those in steam locomotive practise. The problems which the steam locomotive designers have been working on for nearly a century, have been solved electrically. A kind of apparatus was required which had not been built before, combining a great many new types of elements, and a great many elements of common type, but designed in new fashion, so that they can work together on a large scale, and we utterly outdistance steam practise.

If the new locomotives are hauling more coal and giving railway service superior to any ever given before, it is a little uncomplimentary, at least, to say—"Well, that is probably the least unsatisfactory thing that could be done." Of course it is, if we have done the best thing possible, exceeding anything which was done before, of course it is the "least unsatisfactory." That particular system is best which in a given case performs the service at the least cost.

William Arthur: When you stand back and look at what has been accomplished on an electrification such as the Norfolk and Western, you get a new perspective. Talk, such as we have heard about retainers, whether single-phase generation was highly efficient, when compared with some other system, and other relatively unimportant details seems to me very largely immaterial. The weight of the locomotives too, has been compared and one member referring to the locomotives on the Norfolk and Western, mentioned the fact that they had to carry the phase converter. A locomotive must possess weight in order to fulfill its functions. No one can conceive of a weightless locomotive doing any work. You have to get the grip on the rail and sufficient power must be applied to the wheels to maintain the adhesion which the engineers decide is necessary. That today can be done with any system. The question of the weight of the locomotive as between the various systems is today relatively unimportant, although a few years ago when we had only low voltage, direct-current and single-phase, to compare it was of more importance and there was then usually a difference between the weight of the two types for the reason that the low voltage d-c. motor considered alone, will always be lighter than a motor of the same capacity but of the single-phase type.

This is not true to-day of the locomotives as a whole. The problems entering into the weight question, the space problem, the means of ventilation, etc., are such that taking the modern locomotives of the various types and comparing them, there is but very little difference between them. To-day locomotives can be built on any system, particularly for freight service, which have practically the same weight.

H. M. Hobart: I do not share Mr. Behrend's pessimistic view that it is a question of choosing the least unsatisfactory of two very unsatisfactory solutions. I think it is a question of which is the most satisfactory of a variety of excellent solutions. On the other hand, I do not agree with Prof. Scott, and some others, that engineers, can say that the sole test of success is technical success. Engineers must continue to strive to get the best system possible. Because a system works and works excellently, it does not mean that it is the best system, and we will all admit that in the long run the object is to find the most excellent system, and that is decided on the basis of dollars and cents.

It is surely not necessary at this time to review the distinguishing features of each particular system, three-phase, direct-current and single-phase. What has always exasperated me is that we did not sit down ten years ago, or earlier, and actually settle on paper that which could have been absolutely and conclusively settled on paper. I do not for my part see why it should have taken engineers ten years to conclude that the single-phase generator is out of all proportion heavier and more expensive for its output than the three-phase generator. Right up to very recently, whenever in papers or discussions I assigned to the single-phase generator any approach to its actual and now widely admitted degree of inferiority, it was stated that my representations were seriously exaggerated.

Mr. Behrend estimates a superiority of the order of 2 to 1 for a three-phase as compared with a single-phase generator. As I have already stated, it has been very difficult to find recognition of the fact that the inferiority of the single-phase generator is of such magnitude as to be of any consequence. Mr. Behrend, however, recognized this at an early date and it is of interest to recall his statement of ten years ago in an article in *Cassier's Magazine* to the effect that: "The very much reduced output of both generators and motors, if operated single-phase; the reduced efficiency; the impaired regulation; the increased heating and less stability of single-phase motors and generators, connected with the increased cost resulting from the greater amount of material required; these form the main reasons which induce me to call the recent attempts which have been made in the utilization of single-phase currents, a forced idea."

Professor Scott, in alluding to the inferiority of the single-phase generator said: "What of it, it is only one link in the system?" In reference to the greater cost of a locomotive having a phase converter on it, we might say "What of it, it is only one link in the system?" But they all count up, and we must take account of each link. We are not concerned to get the most novel system, or to get something which technically works with great satisfaction, if it is economically inferior. It is quite incumbent on some one, and I have taken upon myself that duty, to remind you of what we all know very well, that the engineer must strive to obtain the most economical result.

F. E. Wynne: I agree with Mr. Hobart that it is very desirable to obtain some figures regarding the economics of operation of all electrifications which have been made. On that question, if he will refer to the last sentence of the paper, he will note that we make the following statement: "Presumably, the railway company will at some time in the future give statistics showing, better than is now possible, the heavy traffic and severe service which electrification is successfully meeting in this installation." When I wrote that I had in mind also the economies of operation on this road. Such information was not available for publication at that time.

One of the best features in the induction motor is its constant speed qualities, which insures adherence to schedules, which the variable speed motor does not necessarily do. Like Mr. Shepard, I used to be very strongly on the other side of the fence, and thought there was no possibility of an induction motor being of any use on a railway. Following the operation of the Italian State Railways, and also having seen the operation on the Norfolk and Western, I must say that I am convinced that it has a very good field, and that the constant speed characteristic is not altogether, in fact, it is very far from being altogether, a disadvantage in this type of engine.

Mr. Shepard stated that the retainers are not used at all on this road for assistance in braking. If any other system of electrification requires the use of retainers in order to get over the brow of the hill, it is certainly a serious handicap to that system. The correction for wheel variation which is mentioned as a possibility has not yet been found necessary in practise. So far the individual motors take whatever unbalancing is found due to difference in wheel diameter. It may be found desirable to stand for the slight rheostatic losses entailed at a later date when the wheels get worn more.

Mr. Behrend's question, which he said he would ask if he dared, was why this installation was not three-phase throughout; that is, three-phase generation, transmission, conversion, distribution, and propulsion. There are two ways in which I think that can be best answered—one is that the Great Northern Cascade Tunnel, three-phase installation, has been in operation for a number of years, and since that time I know of no other case where a three-phase installation has even been proposed, not to say, been installed, in this country. Second, there seems, as Mr. Behrend mentions, to be a decided prejudice against two trolley wires in this country. I think if he would go over the Norfolk and Western electrified zone he would probably also become prejudiced against the use of two wires over each track. It would be an exceedingly complicated piece of overhead work, and as there are nearly one hundred miles of trackage to be handled I hardly see why we should handicap this one hundred miles of track and the problem of collection for the sake of getting two or three more efficient generators and eliminating a certain piece of apparatus from the dozen locomotives.

Prof. Scott's characterization of the split-phase locomotive as using the electrical part of the system to relieve the mechanical part is, I think, very happy. He also inquired as to whether the performance as measured by the train sizes and speeds had ever been equalled in steam operation. So far as I know, it has not. Very frequently there have been larger trains handled, but I do not think that the combination of train size and speed on such grades has ever been secured elsewhere.

Prof. Slichter asked what variation in voltage occurs at the locomotive. So far as I know, the variation has not exceeded 25 per cent, and I think the track capacity together with the distribution layout will hardly ever permit it to exceed this value.

Prof. Slichter also inquired regarding some kind of a shock absorber for regenerated energy. The traffic on any railway of necessity at times will have valleys where there is no load being taken from the power house—it is not peculiar to the Norfolk and Western—and consequently in any system utilizing regenerated energy and supplying railway load alone, it will be necessary to provide at the feeding points, either substations or power house, a rheostat which will absorb the regenerated energy when there is no other load on the line. Such a rheostat is in use on the Norfolk and Western and operates a few times in the course of a day.

In this discussion, there has been a tendency to emphasize details and to determine which present system is the least disadvantageous, or whether any one is the most advantageous. I think that is a biased point of view to take. We are all trying to improve the art of electric railroading, and I believe that every one here will agree that an art which has only thirty years' of history behind it, is not yet perfected. There is probably no one electric railroad system that is as yet perfect. We hope that some day the various systems may be perfected, and that it may be possible to determine for individual cases, which is the most advantageous system; and if such a thing is possible, we should like to see a single system on which we may standardize. I think it will be some years before we get to any such point. Electrification is entirely too new and young at the present time.

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THE LIQUID RHEOSTAT IN LOCOMOTIVE SERVICE

BY A. J. HALL

ABSTRACT OF PAPER

This paper describes the liquid rheostat in locomotive service, giving in detail the arrangement of the mechanical parts and means for controlling it.

LIQUID rheostats in locomotive service were successfully used for the first time in this country to control three-phase induction motors on the Norfolk & Western locomotives, which have certain operating characteristics resembling very closely those of the steam locomotive, especially the manipulation and the amount of abuse they will stand without being materially damaged.

The principal functions required of these rheostats are as follows: To cut out the resistance in the secondary circuit of the main motors while accelerating, or regenerating; to compensate for the slip between the different pairs of motors, due to the variation in the size of drivers, and to make and break the current in the main circuit to reduce wear on the primary switches.

The main circuit schematic diagram, showing the connections of the liquid rheostat in conjunction with the rest of the equipment is shown in Fig. 1.

The rheostats are operated in pairs each pair having one operating mechanism, storage reservoir, cooling tower and circulating pump.

Figs. 2, 3 and 4 show the mechanical structure of the liquid rheostat, which consists of one main casting, which is divided into four compartments, a central one and three arranged in triangular form around it. A set of electrodes is mounted in each of the three outer compartments. In each compartment, one electrode is grounded to the side of the main casting, and the other is suspended from the top cover and insulated from ground by three porcelain insulators. The rods which support the latter electrode are connected by copper straps on the outside of the cover. Each set of electrodes is connected through a pole change-over switch to the secondary of a three-phase motor. The electrolyte furnishes resistance between the insulated electrodes suspended from the cover, and those grounded on the side of the main casting, thus making the main casting the common point of the star connection. The center compartment provides space in which a steel tube, *T* (Fig. 3), which can be raised or lowered, acts as an overflow pipe for the liquid. The height of the liquid in the rheostat is thus varied by the position of the overflow tube. The electrodes are made up of iron plates.

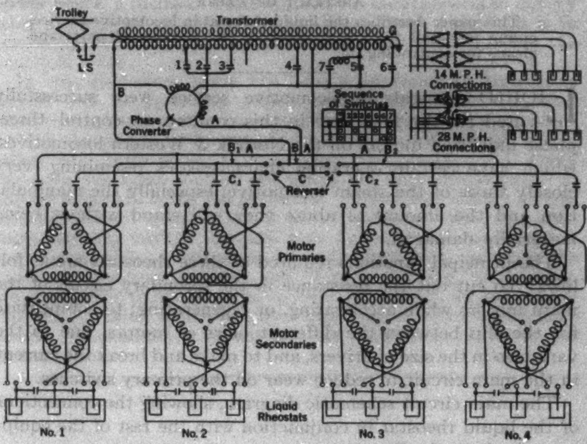
Trolley
Transformer
G
LS
1
2
3
4
7
5
6
B
Phase Converter
A
Sequence of Switches
14 M. P. H. Connections
28 M. P. H. Connections
B₁ A
B A
A B₂
C₁
C
C₂
Reverser
Motor Primaries
Motor Secondaries
Liquid Rheostats
No. 1
No. 2
No. 3
No. 4

Fig. 1—Schematic Diagram of Main Circuits of Single-Phase Locomotive with Liquid Rheostat Control for Induction Motors

The effective area gradually increases and the resistance in the circuit decreases as the surface of the liquid arises.

Two of these rheostats are mounted on top of the main supply tank containing the electrolyte, which consists of a 0.5 to 1 per cent solution of anhydrous sodium carbonate (NA_2 CO_3). The intake to a pump which will circulate approximately 300 gallons (1135 l.) per minute is connected to the supply tank and the outlet is divided into two paths which lead into the bottom of the rheostat castings mounted on top of the supply tank. The upper portion of the regulating or overflow tube (*T*) is about three in.

(7.6 cm.) smaller in diameter than the lower portion, so that when this tube is at its lowest position, there is a space (*S*) around the valve for the liquid to flow through from the rheostat to the supply tank without coming into contact with the electrode. When the overflow tube is raised, the upper portion of the larger part of the tube comes in contact with the valve seat, preventing the liquid from flowing through. It then flows over the top of the tube, raising the level of the electrolyte in the rheostat and submerging a portion of the electrodes. This position is called the " flush-level " of the rheostat.

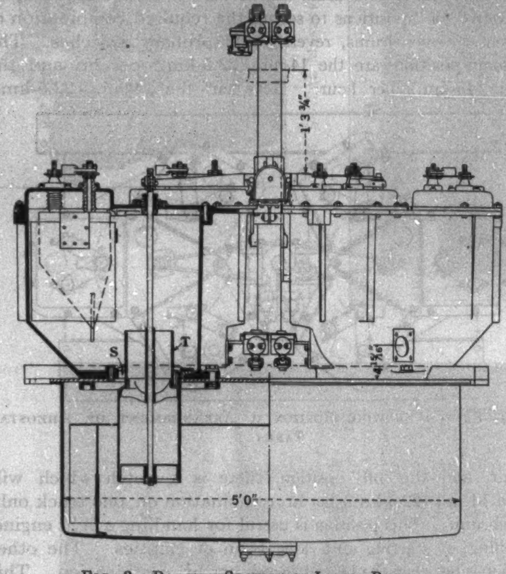

FIG. 3—PARTIAL SECTION OF LIQUID RHEOSTAT

The operating mechanism in the center of the rheostat is controlled by a balanced pressure operating mechanism which is mounted above and between the two rheostats. The crossarm extending from this mechanism is connected to each of the two overflow tubes by a rod. Thus the raising or the lowering of this crossarm raises or lowers the level of the liquid, which in turn varies the surface of the electrodes submerged. The entire control of the locomotive centers about the liquid rheostats, which are so designed that the engineman can bring his locomotive up to speed with practically an infinite number of steps.

The master controller, Fig. 5, consists of two separate and independently operated drums, neither of which is mechanically interlocked with the other, but both are interlocked with the reverse drum, so that both handles must be in the " off " position before the reverse drum can be thrown. The speed drum has four " on " positions to set up the required combination of pole change-over drums, reverser and primary switches. The two main positions are the 14-mi. (22.5-km.) per hr. and the 28-mi. (45-km.) per hour. Between the 14-mi. (22.5-km.) per hr. and the "off" position, there is a notch which will give a 14-mi. (22.5-km.) per hr. combination on one truck only in each unit. This position is useful for handling a light engine, switching, or starting up a long train of empties. The other position is between the 14 and 28 mi. per hr. combination. This is for changing over from 14 to 28 mi. per hr. without losing tractive effort or causing sudden jolts in the train while changing over. The transition is made by first changing over one pair of motors in each unit to 28 mi. per hr., and as soon as the rheostat for these motors has reached the flush level position on the 28-mi. per hr. combination, the speed handle is moved to the full 28-mi. per hr. position, which will thus change over the remaining pair of motors.

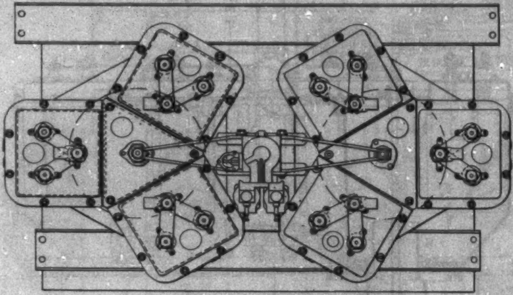

FIG. 4—SKETCH SHOWING HORIZONTAL ARRANGEMENT OF RHEOSTAT TANKS

The accelerating drum has three operating positions, marked

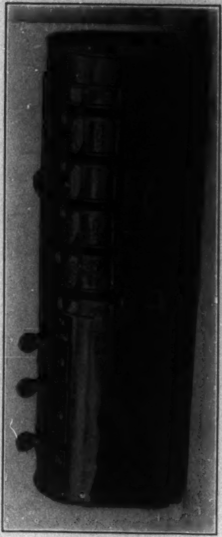

FIG. 6—AUXILIARY CONTROLLER [HALL]

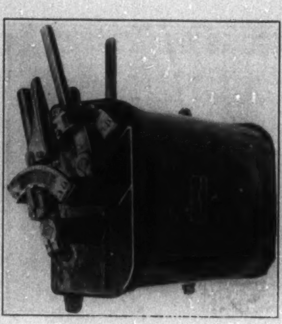

FIG. 5—THE MASTER CONTROLLER [HALL]

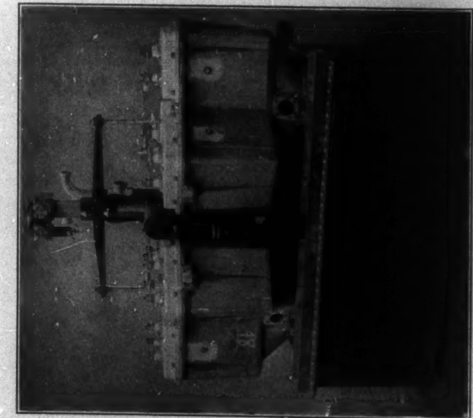

FIG. 2—THE LIQUID RHEOSTAT [HALL]

"lower," "hold," and "raise." These terms refer to the level of the liquid in the rheostat.

In addition to the master controller, an auxiliary controller, Fig. 6, is provided, in which are located levers for the control of the pantagraph, phase converter, etc., and a set of levers by means of which the load on each pair of motors may be governed independently. This independent control is provided so that any difference of load between the various trucks may be corrected, such as that due to difference in wheel diameter, variation in electrolyte, etc. It is also advantageous in the event of one truck slipping its wheels. When this occurs, the torque on this truck can be reduced until the wheels again catch the rail. It can then readily be brought back to full torque without reducing the torque of the remaining drivers.

When the rheostats are full of liquid, the proper short-circuiting switches are closed, short-circuiting the motor secondaries. These short-circuiting switches do not come in until the operating mechanism is in the full " on " position.

Two limit switches are used, one for each speed combination, their function being similar to an overload trip, except that they do not open the main circuit. Should the torque exceed a predetermined amount, the limit switch will open the control circuit of the liquid rheostat operating mechanism, and thus lower the level of the electrolyte, inserting more resistance in the secondary of the motor. These limit switches are especially useful for preventing the motors on the rear locomotive from being overloaded when the train is being brought to a stop.

The cooling tower for electrolyte consists of a series of inclined trays, the liquid flowing over the trays while air is blown over the surface of the liquid to dissipate heat by vaporization. A supply pipe for the cooling tower is connected to the main circulating system near the outlet of the pump. This will by-pass a certain amount of liquid which, after flowing over the surface of the trays, flows back into the supply tank.

The cooling tower operates whenever the locomotive is in service; the rate of cooling varies according to the temperature of the liquid—the hotter the liquid, the more effective the cooling tower becomes.

The results obtained in this severe service, in flexibility of control, capacity and ability to withstand extraordinary duty, have demonstrated conclusively the advantage of this method of control.

DISCUSSION ON "THE LIQUID RHEOSTAT IN LOCOMOTIVE SERVICE" (HALL), NEW YORK, FEBRUARY 9, 1916.

C. D. Knight: The ordinary industrial liquid rheostat, Fig. 1, used considerably for mine hoisting work, consists of a large tank with a chamber at the top containing the electrodes and movable weir, controlled through a system of levers by the hoist operator. The position of this weir determines the level of the water.

An electrically operated pump having usually a capacity of about 300 gallons a minute pumps the electrolyte from the lower part of the tank to the upper chamber in a predetermined period, usually five to twelve seconds. When the weir is brought to its lowest position the upper chamber is emptied, the electrolyte dropping into the lower part of the tank, where its temperature is lowered by means of cooling coils.

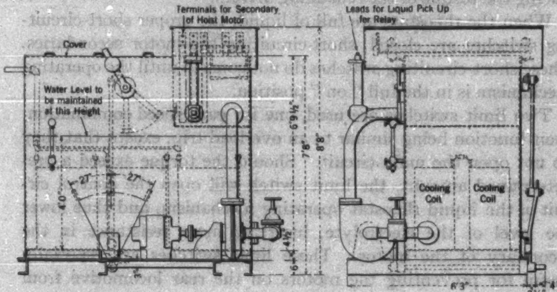
Terminals for Secondary of Hoist Motor
Leads for Liquid Pick Up for Relay
Cover
Water Level to be maintained at this Height
27"
27"
4'0"
6'9½"
7'8"
8'8"
4½"
6"
Cooling Coil
Cooling Coil
6'3"
4½"
3½"

FIG. 1

Mr. Hall has told us that his method of cooling the electrolyte is by running it over a certain number of cooling trays. The capacity of a liquid rheostat depends to a great extent on the safe running temperature at which the electrolyte can be maintained. As Mr. Hall has shown us only the general construction and overall dimensions of his rheostat without any information regarding the cooling trays, I should like very much to have him give some further information with reference to the size and cooling capacity of the trays; also some information regarding the electrical characteristics of this rheostat. In other words, what amperes and volts can be carried for intermittent and continuous duty, as there are very few figures in the paper, which would go to show the actual capacity of the device.

The characteristics of induction motors require more or less resistance in the rotor circuit for relatively long periods, and considerable energy must be dissipated. How much does this amount to, and how much water would be evaporated under operating conditions? He states that in this type of device you can use as much water as you please, bearing in mind that there is a big supply of water for cooling. I should like to know how he keeps a constant solution if he is continually evaporating the electrolyte and refilling the tank with fresh water.

Mr. Hall also states when the rheostats are full of liquid the proper switches are closed, short circuiting the motor secondaries, and that these short-circuiting switches do not come in until the operating mechanism is in the "full on" position. I wish to ask Mr. Hall if he has any interlocking arrangement, which insures that the motor secondaries are not short circuited during the accelerating period of the motor.

R. E. Hellmund: Mr. Knight asked how large the cooling tower for the water is. As far as I remember, each of the cooling towers in which the water runs down and the air goes up, is about four to five feet high, two to three feet wide, and two feet six deep. It is very small as compared with anything else that could be done. The reason, as mentioned in the paper, is that the water evaporates and heat is dissipated in that manner.

Regarding the capacity of the tower, I might say that at times the rheostat for one of the cooling towers takes care of 800 amperes with about 750 volts to start with during accelerations for periods of five or ten minutes, or even longer, and I have also seen it operate for periods of ten or fifteen minutes at one time; when the signals are against the train these loads are often repeated several times without causing trouble of any kind. The only difference that can be noticed under such severe conditions is that some steam comes out of the cooling tower exhaust.

As mentioned by Mr. Knight, the evaporation of the water will, as a matter of course, change the solution, but we find that the rheostat is not at all sensitive in that respect, and by adding a few gallons of water about once in twenty-four hours, it can easily be taken care of.

Mr. Knight asked if there was any interlocking system which assures that the short-circuiting switches do not come in until the water is at high level. There is such an interlocking system, consisting of contacts which are located at the top of the rheostat, and are closed by the water when it gets there. This insures the reliable operation of the rheostat.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 9, 1916.

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CHATTERING WHEEL SLIP IN ELECTRIC MOTIVE POWER

BY G. M. EATON

Abstract of Paper

The paper shows that chattering wheel slip is characteristic of all types of electric motive power. The application of the motive power in the electric and steam drives is compared, and the reasons for the chattering wheel slip and the means of measuring and rectifying the same are given.

WHEN THE steam pressure in the cylinders of steam motive power is high enough to start slipping of drive wheels, their acceleration is fairly uniform and rapid, the load on the piston being well sustained on account of late cut-off and stored steam in pipes, receivers, etc.

In contrast to this, with electric motive power, regardless of the method of transmitting the tractive effort from the rotors to the wheels, the acceleration after slipping starts is liable to be erratic, being dependent upon the distribution of rotating masses, and upon the characteristic of the coefficient of friction between wheel and rail.

The fundamental difference between the running gear of steam and electric motive power is that in the steam locomotive, the only moving parts having relatively high moment of inertia are the driving wheels.

In an electric locomotive, the moment of inertia of the rotors, especially when operating through a gear reduction, may be as great as or greater than that of the driving wheels.

The combined inertia of connecting rods, cross-heads, piston rods and pistons is practically negligible as far as it affects acceleration of driving wheels after slipping starts. In an electric locomotive, when slipping occurs, the sequence of events is as follows, regardless of the type of drive:

Current is applied to the motor and the rotor starts to turn. Clearances in the entire transmission mechanism are first eliminated. Then, as the torque is increased, the metal of the transmission, framing, etc., is bent and twisted, or otherwise deflected. This stressed metal becomes a storage battery of energy. Finally the tractive effort reaches a value sufficient to overcome the existing adhesion at the rail (coefficient of friction of repose), and the wheel starts to slip. The instant relative movement occurs between wheel and rail, the coefficient of friction drops from that of repose to that of relative motion. There is, therefore, an opportunity for the stressed metal to start discharging its stored energy, since part of the resisting force has disappeared. This energy is expended in accelerating the wheels ahead of the angular position they occupied relative to the rotor at the instant slipping started.

It is necessary next to analyze independently the two divisions of the rotating system, namely, rotors and wheels.

Since the wheels are being accelerated ahead of the rotors, the rotors are losing their load and will tend to speed up. This is true not only of motors of series characteristic, but also of induction motors when running below synchronism, as will ordinarily be the case in traction work when the wheels slip. In fact, the induction motors, because their generated counter e. m. f. with increased speed is less than with series motors, will hold up their torque better and, therefore, accelerate faster. The induction motor, in this particular, more nearly approaches the steam locomotive, in which, at starting, steam is cut off as late as possible in the stroke, so as to get the maximum starting tractive effort.

Analyzing next the other division of the system, the adhesion at the rail will decrease as the velocity of the wheel tread relative to the rail, increases. The effort being transmitted through the transmission system, however, will decrease very rapidly, due to expenditure of stored energy, and as soon as this effort, which is tending to accelerate the wheels, becomes less than the adhesion at the rail, which is tending to retard the wheels, the wheels will evidently start to slow down.

There are, then, two sets of rotating masses mechanically coupled, the masses at one end of the system accelerating, and those at the other end, retarding. As soon as clearances in the transmission are taken up, there is liable to be a jolt on the mechanical system, accompanied by a recoil. This gives the setting for chattering action, and such action has been experienced in practically every type of electrically-driven rolling stock where the motors are sufficiently powerful to slip the wheels at high adhesion.

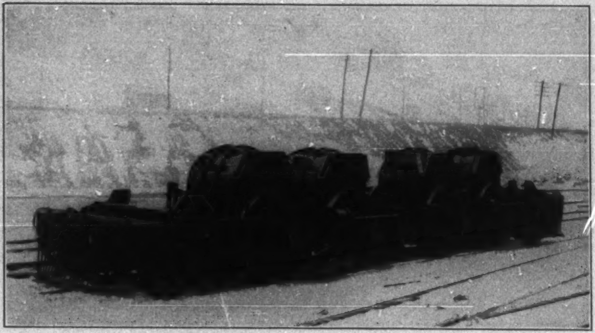

FIG. 1 [EATON]

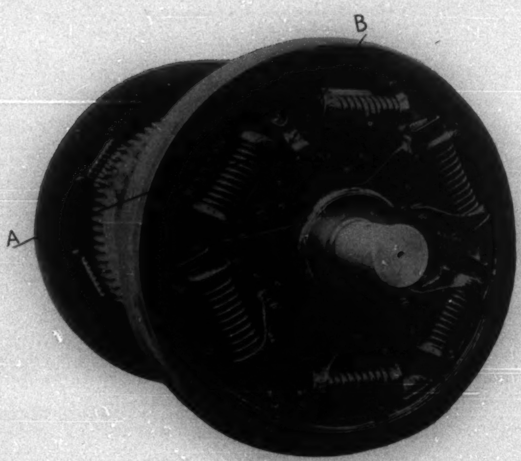

FIG. 2 [EATON]

FIG. 3 [EATON]

FIG. 4 [EATON]

Vol. 35
1916

This occurred on the geared freight and passenger locomotives whose transmission is shown in Fig. 1. The quill arms at the point marked *A* hit against the wheel spokes at the point marked *B*, Fig. 2, and more or less breakage of these arms occurred. It was found, however, that the arms which broke had blow-holes in the interior of the castings, and after these defective castings were eliminated, the breakage practically ceased.

In later locomotives in the same service equipped with two motors per axle, the change in armature inertia eliminated this striking. Chattering slip still occurred, but the capacity of the quill springs was sufficient to limit the amplitude of swing to a distance less than the existing clearances.

A certain amount of similar striking again occurred in some switching locomotives, but here again the parts were strong enough to stand the service.

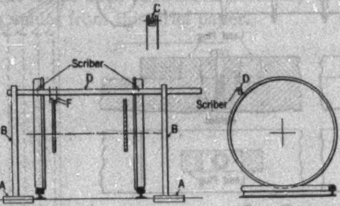

FIG. 5—HAND-OPERATED DEVICES FOR RECORDING CHATTERING SLIP

The same characteristic is occasionally observed in city and interurban cars, although this is much less frequent than in heavy hauling electric locomotives. This is due to the greater tractive power in proportion to the weight which is employed in the latter type of motive power.

In case of freight locomotives where the motors are geared directly to the axles the same phenomenon has been observed.

On the Norfolk and Western locomotives, chattering slip occurred in the running gear shown in Fig. 3. After the locomotives had been in service for some months, evidences of failure were detected in the crank pins. The cause was traced to chattering slip by means of a rough oscillograph, as shown in Fig. 5. The brakes were set on three trucks, and the oscillograph frame was set up on the fourth truck. The wheel tread was chalked. The oscillograph frame was oscillated about its supporting points *A*, Fig. 5, the amplitude of oscillation being two inches. The time of complete oscillation was two seconds. The scribers were pressed against the wheel tread. The wheel treads were then slipped, and the characteristic diagram of the chattering slip was obtained, as shown in Fig. 6. The analysis in the figure is self-explanatory. By means of this diagram, it was possible to figure approximately the forces necessary to produce the acceleration and retardation which occurred, and the resultant stresses in the rods, pins, etc., were calculated.

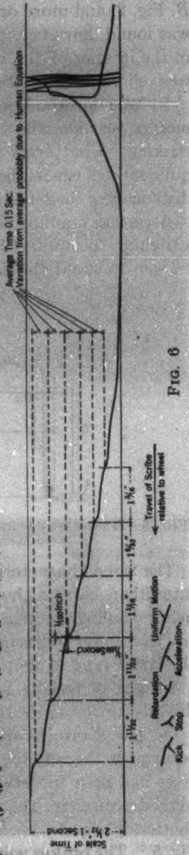

FIG. 6

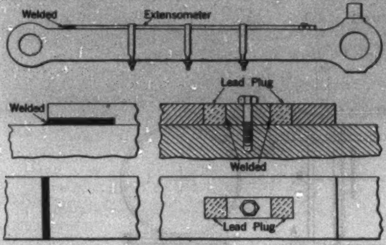

FIG. 7

To check the oscillograph figures, extensometers were arranged, as shown in Fig. 7, by means of which the connecting rods indicated their own stresses. The extension and compression of the rods were recorded by means of the compression of blocks of lead. This is evident from a little study of the figure.

The two methods checked within a very few per cent. On the basis of the results, new rods, pins, etc., were applied on the locomotives. These have proved adequate for the service.

This chattering slip was more evident on the Norfolk and Western locomotives than could have been anticipated, since this was the first time electric haulage had been applied in service where such extremely high tractive efforts were required.

The phenomenon had never been observed on the locomotives with transmission as shown in Fig. 4. After it was experienced on the Norfolk and Western, however, permission was secured to make a test on the locomotives shown in Fig. 4. The wheels were slipped several times in succession in the same spot on the rails, and on the third slip, chattering occurred.

In all heavy hauling electric motive power, this problem must be considered, with every type of drive. The great number of variables entering and the wide fluctuation of certain of these variables render broad experience necessary in securing a successful solution of the problem. This has been gone into deeply and quantitatively by the writer and his associates, together with engineers of the locomotive works, with elaborate special testing apparatus, but it has been considered necessary to eliminate all quantitative values from this brief paper.

DISCUSSION ON "CHATTERING WHEEL SLIP IN ELECTRIC MOTIVE POWER" (EATON), NEW YORK, FEBRUARY 9, 1916.

S. T. Dodd: It occurs to me that chattering wheel slip is exactly the same phenomenon which has been reported on a good many European side-rod locomotives. Of course, the European designers have had more experience than we have had in designing various types of side-rod locomotives, and there have been reported in the foreign technical press several failures of this type of locomotive. I have in mind principally a couple of reports in German papers in regard to the Loetchberg locomotives. These locomotives, as you will remember, have characteristics which would increase the possibility of such a thing occurring. They have two very large motors of about 1300 h.p. each, geared to jack shafts the jack shafts tied together by Scotch yokes, which in turn are connected to the driving axles by side rods. In the papers I have in mind, they describe the disturbance in these locomotives, as a "shuddering" motion occurring at speeds of 20 to 25 miles an hour. This is so intense as to break the cranks and the Scotch yokes, sometimes by tearing them apart by tension, and sometimes crushing them by compression. The papers I have made reference to discuss mathematically the motions and the stresses which occur in such a frame work as that, showing that these forces are proably due to the building up of mechanical resonance between the springing of the driving rod on one side, and the inertia of the very heavy armatures on the other.

As far as I can see, that is what Mr. Eaton describes in his paper, in clear physical language, where the German writers describe it mathematically. The cure which the mathematical analysis pointed out was the introduction of springs of considerable amplitude of motion as compared with the amount of displacement you would ordinarily get in the side rods. By inserting springs whose amplitude of motion could be measured in inches rather than in thousandths of an inch, they expected to eradicate these troubles. For the Loetchburg locomotives, spring gears were ordered sometime before the European war, but I have never heard that they were installed, or the results if they were installed.

The question which occurs to me is whether Mr. Eaton's chattering wheel slip is not another phase of exactly the same phenomena which appeared on the Loetchburg road and on many of the European locomotives, and whether a cure for it would not be found in exactly the same thing which was found as a cure for the European locomotives, that is, the introduction of a certain amount of spring, with a certain amplitude of motion and, with a dead beat action which would damp out these oscillations before they could build up to any considerable extent.

W. I. Slichter: About ten years ago I was called on to make some calculations as to the effect of the pulsating torque of single-phase motors on the gears and transmission between the motors and wheels, and when I got my equation of friction, inertia and mass and elasticity of the material, I found I had an equation like that of a single-phase circuit, with resistance, inductance capacitance, and as soon as I had the equation I saw the solution—change the inductance or capacitance so you no longer have resonance, and the chattering would disappear.

Charles F. Scott: About six months ago Mr. Eaton was called down to the West Virginia mountains by telegraph to diagnose this difficulty described in the paper. He found that the wheels were slipping. His problem was to find out why they were slipping, and what to do to prevent it.

He had at hand for his investigation of this oscillation all the refinements of the railway repair shop for supplying his physical apparatus, and his own initiative and ingenuity for devising the means of proceeding with the facilities at hand. The oscillations were scratched on a long strip of iron about 1/32 of an inch thick, and three or four inches wide, attached to the circumference of the driver. A sharp point was drawn across when the wheel began to slip. He had to try a good many times to get a record, and his actual record was a little scratch line on the rough piece of iron. Then taking that little wavy line, drawing tangents to it, getting the change in the rate of acceleration at different times and taking the moment of inertia of the wheel, he calculated the forces required for producing the recorded acceleration. Apparently, it was a very coarse, crude method.

Looking at that connecting rod, you would think if anything was solid and would stay together, it would be that great big steel rod. It is apparently quite a number of inches wide and several inches thick. He wanted to find out how much the rod was being stretched, and what was the variation in length of the rod during the slipping. That kind of measurement would ordinarily require microscopes, and other apparatus which a well equipped physical laboratory would afford. He proceeded to the repair shop and got a strip of iron and riveted it to the rod at one end—and attached it by a piece of lead at the other end. After this rod had gone through its vibration, he finds that the lead has changed a little in size, showing the amount of change of length between the great big side rod and the little constant length rod attached to it. Then from this elementary, simple method of measurement, he finds a very close agreement with the measurements made with scriber on the circumference of the driver.

W. L. Merrill: This same phenomenon has been known and has given trouble for years in ordinary metal cutting, that is, I refer to lathes, principally. Now, undoubtedly the tires of the locomotives we have been discussing here had the same trouble develop when they were being turned up, if too hard a cut was taken. The matter is not serious, except in some kinds of drive. For example, a punching press which is foot operated; that is, a fly-wheel is running all the time and the clutch thrown by a lever, if the press is driven by an individual motor, and this motor is controlled by an automatic starter, which depends on current flowing through some part of the mechanism for holding home the controller or the starter in the full-on position. If we have a heavy cut to make with this press, upon the releasing of the load as the die travels through the stock, the twist or whatever you gentlemen choose to call it, that is put in the gearing mechanism at the time the fly-wheel is giving up its energy is immediately reversed the other way, and the current reverses through the motor, the motor shuts down and the machine stops. That is a simple matter and can be taken care of by putting on a type of starter which depends on voltage instead of current for holding it in position.

The same thing occurs on lathes, when driven through the back gear, and several sets of gearing between the point of application of power which may be a belt, if too heavy cuts are taken or the angle of the tool is ground improperly.

I mention that as being exactly the same thing as what we are discussing in the slippage of the wheels.

G. M. Eaton: Referring to Mr. Dodd's discussion, there is a point of inherent difference between the chattering which occurs at the time that the wheels are slipping, and the "shuddering" which Mr. Dodd refers to as having occured in various rod-connected European locomotives. This "shuddering" is a true synchronous action occurring at a certain critical speed, and at higher multiples of this critical speed. When this "shuddering" takes place on a given locomotive and at a given speed, it is of a practically uniform frequency. Contrasted with this, the chattering occurring when the wheels slip, may be over a surprisingly wide range of frequency. The writer has observed it, (at a frequency per second of 3½, about 4, about 5, about 6, and up to as high as 33), on a given locomotive under conditions where the only observable difference was a probable variation in co-efficients of friction between the drive wheels and the rail.

This erratic action can be explained only by the presence of at least one very widely varying function, and this condition is met by the characteristics of friction between the rail and the drive wheel.

The illustration brought out by Mr. Merrill fits very much better. In a lathe, the action of the tool in producing the chip may cause alternate smooth running and breaking of the chip, and this will provide the necessary setting for production of vibration. There are two or three other actions which may occur and give the necessary conditions. Cuts of various depths will alter the frequency.

Chattering wheel slip has occurred in various locomotives where true resonance at high-speed running has never occurred, thus showing conclusively that the setting is different for the production of erratic chattering slip, and true resonance.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 9, 1916.

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A METHOD OF DETERMINING THE CORRECTNESS OF POLYPHASE WATTMETER CONNECTIONS

BY W. B. KOUWENHOVEN

Abstract of Paper

The object of this paper is to describe a method of checking the correctness of the connections of a polyphase watt-hour meter on a three-phase circuit; and to show that the methods most commonly used for this purpose are unreliable. Polyphase wattmeters are classified according to the number of their voltage terminals and expressions giving the amount of energy theoretically registered by the meter are derived for all possible arrangements of the connections for each class. The correctness of these expressions was checked experimentally. The expressions are given in the form of tables. A study of these tables reveals the fact that the methods of checking the connections in most common use are unreliable. A method is developed which may be relied upon to check the correctness of the meter connections on a balanced three-phase circuit at any power factor. Rules are worked out from this method, that make the rectification of incorrect connections simple. In addition to this, another method is described which may be used on balanced or unbalanced three-phase circuits at any power factor, provided the opening of one phase at a time is permissible.

THIS PAPER describes a method for ascertaining the correctness of the connections of a polyphase wattmeter on a three-phase circuit.

The accurate measurement of electric power is very important, and on three-phase circuits polyphase wattmeters have come into general use for this purpose. The liability of making mistakes in the connections when installing these meters is well known and several methods of checking the connections are in use. Articles on this subject have appeared in the *Electric Journal** and in other publications, and the National Electric Light Association devotes several pages of its handbook to a description of methods for checking the connections. A canvass of some thirty power companies throughout the country brought out the fact that almost the only method of checking the connections in actual use is that of opening the voltage or current supply of each element of the meter in turn and noting the direction of rotation. This should be in the right direction if the power factor is above 0.5. However, not only is the above check unreliable, but also none of the other simple checks in use may be completely relied upon in identifying the correctness of the connections. It is possible for the meter to satisfy these checks and still be incorrectly connected. For this reason the writer undertook the study of the connections of a polyphase wattmeter.

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* See Bibliography at end of paper.

A study of all the possible arrangements of the connections was made, and the direction and rate of rotation of the disk was determined theoretically for each arrangement. The theoretical results were also checked experimentally. A simple method of checking the correctness of the connections of a polyphase meter on a three-phase balanced circuit at any power factor was developed from the results.[1] The assumption of a balanced load is justified by the fact that every customer requiring a polyphase wattmeter has at least one three-phase motor. Although the discussion is confined to watt-hour meters, the results apply equally well to other similar meters.

THE INVESTIGATION

It is a well-known fact that a polyphase watt-hour meter consists of two separate single-phase elements acting upon a common shaft. Each element is provided with separate current and usually separate voltage terminals, and for the purpose of this investigation the meters are classified according to the number of voltage terminals provided.

Class A contains those meters which have two voltage terminals for each voltage coil, or four voltage terminals in all. Meters of this class may be used with or without voltage transformers.

Class B contains those meters which have but three voltage terminals. On these meters the ends of the voltage coils that are at the same potential are connected together and brought out to a common terminal. This class of meters may also be used with or without voltage transformers.

Often in practise, especially when potential transformers are used, the two voltage terminals of a Class A meter that are at the same potential are connected together. In such cases meters with four voltage terminals belong to the Class B type of instruments.

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[1] After the completion of the paper the writer learned that the method developed is not new. However, no mention of it was found in technical publications.

Class C contains those meters which have but one voltage terminal. This terminal is the common terminal referred to in Class B. In Class C meters, the other end of each voltage coil is connected to one end of the corresponding current coil and brought out to a single terminal. Meters belonging to this class are seldom used with either voltage or current transformers and are usually of the house type.

The number of possible arrangements of the connections is different for each class and therefore each class was considered separately. The number of different arrangements of the voltage connections is given by the expression

$$y = \underline{/x}$$

where x is the number of voltage terminals of the meter and y the number of different arrangements of the connections to these terminals possible. For each arrangement of the voltage terminals, there are sixteen arrangements or combinations that may be formed by the current connections and by the opening of the voltage leads. These are as follows:

(a) Phase I and phase II connected correctly
(b) Phase I reversed, phase II correct
(c) Phase I correct, phase II reversed
(d) Phase I and phase II reversed
(e) Phase I and phase II correct, voltage lead 1 open
(f) Phase I and phase II correct, voltage lead 2 open
(g) Phase I and phase II correct, voltage lead 3 open
(h) Phase I reversed, phase II correct, voltage lead 1 open
(i) Phase I reversed, phase II correct, voltage lead 2 open
(j) Phase I reversed, phase II correct, voltage lead 3 open
(k) Phase I correct, phase II reversed, voltage lead 1 open
(l) Phase I correct, phase II reversed, voltage lead 2 open
(m) Phase I correct, phase II reversed, voltage lead 3 open
(n) Phase I and phase II reversed, voltage lead 1 open
(o) Phase I and phase II reversed voltage lead 2 open
(p) Phase I and phase II reversed, voltage lead 3 open

The presence or absence of current transformers does not in any way affect the number of arrangements of connections. However, this is not true of voltage transformers; and where their presence introduces additional arrangements of connections, their action was studied.

CLASS A METERS

The correct connections of the Class A type of polyphase meter when used without voltage transformers is shown in Fig. 1.

Phases I and II of the three-phase line contain the current transformers which supply current to the current coils I and II of the meter, respectively.

(In all of the figures used in this paper, the current coils are placed horizontally and numbered with the Roman numerals I and II. The voltage coils are placed at right angles to the current coils, and their terminals are numbered according to the three-phase line to which they are connected.)

The number of possible arrangements of the voltage connections to the four meter terminals are in this case given by the expression

$$y = \frac{\underline{|x}}{\underline{|2}}$$

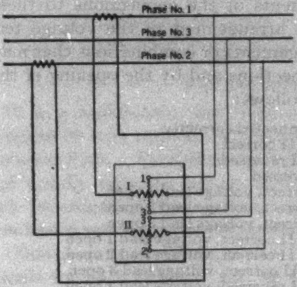

Fig. 1

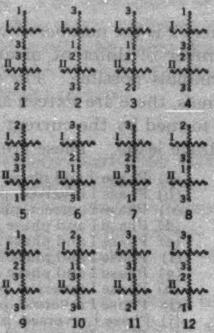

Fig. 2

as two of the voltage terminals are connected to the same phase. Substituting the value of x we find that there are 12 possible arrangements of the connections. These are shown diagrammatically in Fig. 2.

There are also 24 additional arrangements of the voltage connections possible. Twelve of these are formed by connecting two of the meter terminals to phase 1, one terminal to phase 2, and one to phase 3; the other twelve are formed by connecting two meter terminals to phase 2, and to phase 1, and one to phase 3. All of these arrangements are incorrect. They are treated in Tables VIII and IX.

The first eight of these arrangements, Fig. 2, illustrate not only the correct connections, but also mistakes that are more or less commonly made. Wrong connections as illustrated by the last four arrangements of connections are practically impossible except in meters where the terminals belonging to each element are not readily identified. Such connections are just as improbable as the connections of the leads of a current transformer to the terminals of the different current coils. They have been included in this investigation only for the sake of completeness, and to prove that mistakes of this character may be eliminated by the method that will be outlined for the checking of connections.

As each arrangement of voltage connections has 16 possible arrangements or combinations of the connections of the current coils, and opening the voltage leads, we have a total of 192 theoretically different possible connections for this class of meter when used without voltage transformers.

CALCULATION OF THE THEORETICAL EXPRESSIONS

In order to study the effect of any one of the 192 connections upon the operation of the meter it was necessary to derive the theoretical expression for each case, from which the rate of rotation of the disk could be calculated for any load. The following examples serve to illustrate the method followed and the meaning of the expressions found.

Let P = the reading of the polyphase watt-hour meter.

E = the line voltage

E_1, E_2, E_3, I_1, I_2 and I_3, represent the phase voltages and currents respectively.

Φ_1, Φ_2 and Φ_3 represent the phase angles respectively. For the purpose of calculations we shall assume a balanced load with lagging power factor, and that the system is star-connected. Then we have

$$E_1 = E_2, = E_3,$$

$$E_{1,3} = E_{2,3} = E_{1,2} = E$$

$$I_1 = I_2, = I_3, = I$$

$$\text{and } \Phi_1 = \Phi_2, = \Phi_3, = \Phi$$

The power of the circuit is given by the expression $(+\sqrt{3}\cos\Phi)\,I\,E$.

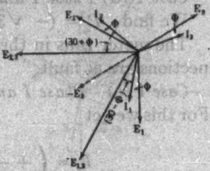

FIG. 3

Calculation of the Value of P for the Case 1 (*a*);
Phase I and II Correct.

The meter is connected as in Fig. 1 and the vector diagram of the circuit is shown in Fig. 3.

Now,

$$P = I_1\,E_{1,3}\cos\,(3\,0 - \Phi) + I_2\,E_{2,3}\cos\,(30 + \Phi)$$

$$= I\,E\left(\frac{\sqrt{3}}{2}\cos\Phi + \frac{1}{2}\sin\Phi\right)$$

$$+ I\,E\left(\frac{\sqrt{3}}{2}\cos\Phi - \frac{1}{2}\sin\Phi\right)$$

We find that $P = (+\ \sqrt{3}\cos\Phi)\ I\,E$

The value of P equals the actual power of the circuit and therefore the connections, case 1 (a), are correct and the meter registers correctly the power consumed. It must be kept in mind that the use of the term correct applies to the connections only and not to the calibration of the instrument.

Case 1 (b) *Phase I Reversed, Phase II Correct.*

We have now for P the expression

$$P = -\ I_1\,E_{1,3}\cos\,(30 - \Phi) + I_2\,E_{2,3}\cos\,(30 + \Phi)$$

$$P = (-\ \sin\Phi)\ I\,E$$

The meter does not register correctly and will run in the wrong direction with lagging currents. At unity power factor it will not run. The connections are therefore incorrect.

Case 1 (c) *Phase I Correct, Phase II Reversed.*

We find that $P = (+\sin\Phi)\ I\,E$

The meter will run in the right direction but not at the correct speed. The connections are therefore incorrect. At unity power factor the meter will not register.

Case 1 (d) *Phase I and Phase II Reversed.*

We find $P = (-\ \sqrt{3}\cos\Phi)\ I\,E$

The meter runs in the wrong direction and therefore the connections are at fault.

Case 1 (e) *Phase I and Phase II Correct, Voltage Lead* 1 *Open.* For this we get

$$P = \left(+\frac{\sqrt{3}}{2}\cos\Phi - \frac{1}{2}\sin\Phi\right) I\,E$$

The direction of rotation will change from right to wrong when the power factor changes from values above 0.5 to values below 0.5. The connections are incorrect.

Case 1 (f) *Phase I and Phase II Correct, Voltage Lead* 2 *Open.* P becomes

$$P = \left(+\frac{\sqrt{3}}{2}\cos\Phi + \frac{1}{2}\sin\Phi\right) I\,E$$

The meter runs in the right direction, but does not register correctly.

Case 1 (g) *Phase I and Phase II Correct, Voltage Lead* 3 *Open.* For this case the value of P is indefinite. It may have the same value as 1 (e) or 1 (f) depending upon which of the leads 3 is open; or it may equal zero if both of them are open simultaneously. Therefore this case does not exist as a special case for this type of meter.

The above examples of the derivation of the theoretical expressions for P, with the addition of cases 2 (d), 6 (a) and 9 (a), will serve fully to illustrate the method of derivation.

Case 2 (d) *Phase I and Phase II Reversed.*

We find that

$$P = -\,I_1\,E_{3,1}\cos\{\pi - (30 - \Phi)\} - I_2\,E_{3,2}\cos\{\pi - (30 + \Phi)\}$$

$$P = (+\sqrt{3}\cos\Phi)\;I\,E$$

The meter will run in the right direction and register correctly the power, therefore the connections of case 2 (d) are correct.

Case 6 (a) *Phase I and Phase II correct.*

The vector diagram for this arrangement of connections is given in Fig. 4.

$$P = I_1\,E_{3,2}\cos(90 + \Phi) + I_2\,E_{3,1}\cos(90 - \Phi)$$
$$P = 0$$

The meter will not rotate and the connections are incorrect.

Case 9 (a) *Phase I and Phase II Correct.*

$$P = I_1\,E_{1,2}\cos(30 + \Phi) + 0$$

$$P = \left(+\frac{\sqrt{3}}{2}\cos\Phi - \frac{1}{2}\sin\Phi\right) I\,E$$

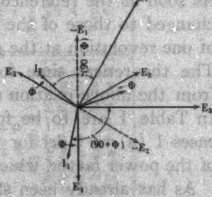

FIG. 4

The theoretical value of P for each one of the cases is given in Table II. The expressions are given in brackets and in every case the common term $I\,E$ has been omitted from the table.

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Due to the fact that cases (g), (j), (m) and (p) are considered as non-existent, we have only 144 different cases or arrangements of connections for class A meters.

EXPERIMENTAL VERIFICATION OF THE FORMULAS

The correctness of the formulas was checked experimentally. The connections of a polyphase watt-hour meter were arranged in all of the possible combinations, and for each arrangement or case, the time of one revolution was determined at several different loads and power factors. The theoretical time was calculated from the derived expression for the given case, and the measured and theoretical results were compared.

The load consisted of a three-phase synchronous converter. The power factor was varied by changing the field excitation and was determined from ammeter, voltmeter and wattmeter readings and was also checked by means of a polyphase power factor meter. Due to changes in the line voltage and to other factors the load could not be maintained exactly constant, and an exact check between measured and calculated results was therefore not always possible.

As the time of one revolution is inversely proportional to the load, we have the relation

$$\frac{\text{Time of one revolution, Case.....}}{\text{Time of one revolution, Case 1 (a)}} = \frac{\text{Expression for Case 1 (a)}}{\text{Expression for Case.....}}$$

For each load and power factor, the time of one revolution in seconds was measured with the meter connected correctly. This time was called the reference time and was frequently checked. As soon as the reference time was found, the connections were changed to those of the case under consideration and the time of one revolution at the given load and power factor measured. The theoretical time for the given case was then calculated from the above relation and compared with the measured time. In Table I are to be found the results of the tests made for cases 1 (a) to 1 (k) for three different loads at different values of the power factor, which was in all cases lagging.

As has already been stated, Table II contains the expressions found for *P* for each of the 144 cases. These expressions were calculated under the assumption that the current was lagging. However, in order to adapt the expressions for use in instances where the current is leading, all that is necessary is to multiply

TABLE I

Case	Expression	Run 1. Power Factor = 1.0 Time of 1 rev. at this load, meter connected correctly = 14.4 sec.				Run 2. Power factor = 0.81 Time of 1 rev. at this load, meter connected correctly = 13.0 sec.				Run 3. Power factor = 0.42 Time of 1 rev. at this load, meter connected correctly = 12.2 sec.			
		Direction of Rotation		Time of 1 rev. sec.		Direction of Rotation		Time of 1 rev. sec.		Direction of Rotation.		Time of 1 rev. sec.	
		Theor.	Actual	Theor.	Meas.	Theor.	Actual	Theor.	Meas.	Theor.	Actual	Theor.	Meas.
1 (a)	$(+\sqrt{3}\cos\Phi)$	Right	Right	14.4	14.4	Right	Right	13.0	13.0	Right	Right	12.2	12.2
1 (b)	$(-\sin\Phi)$	None	None	∞	∞	Wrong	Wrong	31.6	32.4	Wrong	Wrong	9.8	9.8
1 (c)	$(+\sin\Phi)$	"	"	"	"	Right	Right	31.6	30.4	Right	Right	9.8	9.7
1 (d)	$(-\sqrt{3}\cos\Phi)$	Wrong	Wrong	14.4	14.5	Wrong	Wrong	13.0	12.2	Wrong	Wrong	12.2	12.2
1 (e)	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$	Right	Right	28.8	29.2	Right	Right	44.5	48.	Wrong	Wrong	99.	100.
1 (f)	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$	"	"	28.8	30.2	"	"	18.4	18.2	Right	Right	10.8	10.8
1 (h)	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$	"	"	28.8	28.8	"	"	44.5	47.6	Wrong	Wrong	99	102.
1 (i)	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$	Wrong	Wrong	28.8	30.0	Wrong	Wrong	18.4	18.4	"	"	10.8	10.8
1 (k)	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$	"	"	28.8	29.0	"	"	44.5	48.0	Right	Right	99	103.5

the sine terms by (− 1). The table also gives the direction of rotation of the disk for four different values of lagging power factor with each arrangement of connections. By the use of the table it is also possible in cases where incorrect or open connections are found, to determine from the meter readings, when the conditions of the circuit are known, the actual kilowatt-hours that have been used.

Checking the Connections

From Table II we see that there are 64 cases or arrangements of connections where the meter will run in the right direction at some value of the power factor between unity and zero lagging. Forty of these 64 occur on open circuits and 24 when all circuits are intact. As all meters and instrument transformers are tested for open circuits before they are installed, these 24 cases are the important ones. We must therefore consider the problem of ascertaining some simple means for the identification of the correct connections among the 24 arrangements. We also learn from the table that there are four arrangements of connections which give correctly the power passing through the meter. These four correct arrangements of connections are 1 (a), 2 (d), 3 (b) and 4 (c).

One of the most common methods in use for checking the correctness of the connections has been to open the current or voltage supply of first one element and then the other, noting the direction of rotation in each case. For power factors above 0.5 this should give rotation in the right direction for either element, and for below that value, in the right direction for one element and in the wrong direction for the other. A study of Table II shows that this is true for the four correct cases 1 (a), 2 (d), 3 (b) and 4 (c), and that at unity power factor it serves to eliminate all incorrect connections. Further study, however, shows that for power factors above 0.5 and below unity there are four other cases, 5 (c), 6 (b), 7 (d) and 8 (a), which also give continued rotation in the right direction when the voltage supply to either element is opened, and also that at 0.5 power factor there are four incorrect connections, namely, 1 (c), 2 (b), 3 (d) and 4 (c), which give the same indications when the voltage supply is opened, as the correct connections. We also find that the test may be relied upon for power factor below 0.5. A knowledge of the power factor is essential for its application.

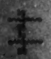
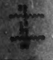
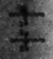
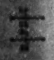
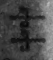
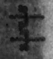
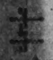
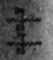
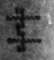
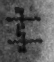
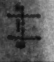
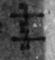
Arrangement	Power Factor	(a) Phase I correct " II " Voltage Leads intact.	(b) Phase I reversed " II correct Voltage Leads intact.	(c) Phase I correct " II reversed Voltage Leads intact.	(d) Phase I reversed " II " Voltage Leads intact.	(e) Phase I correct " II " Voltage Lead 1 open.	Phase I " II Voltage
1 	1.0 <1. & > .5 .5 < .5	$(+\sqrt{3}\cos\Phi)$ Right " " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	$(-\sqrt{3}\cos\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}$ c R
2 	1.0 <1. & > .5 5 < .5	$(-\sqrt{3}\cos\Phi)$ Wrong " " "	$(+\sin\Phi)$ Stop Right " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\sqrt{3}\cos\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}$ c W
3 	1.0 <1. & >.5 .5 >.5	$(-\sin\Phi)$ Stop Wrong " "	$(+\sqrt{3}\cos\Phi)$ Right " " "	$(-\sqrt{3}\cos\Phi)$ Wrong " " "	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}$ c W
4 	1.0 < 1. & > .5 .5 >.5	$(+\sin\Phi)$ Stop Right " "	$(-\sqrt{3}\cos\Phi)$ Wrong " " "	$(+\sqrt{3}\cos\Phi)$ Right " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}$ c
5 	1.0 <1. & >.5 .5 < .5	(0) Stop " " "	$(-2\sin\Phi)$ Stop Wrong " "	$(+2\sin\Phi)$ Stop Right " "	(0) Stop " " "	$(+\sin\Phi)$ Stop Right " "	(—
6 	1.0 < 1. & > .5 .5 < .5	(0) Stop " " "	$(+2\sin\Phi)$ Stop Right " "	$(-2\sin\Phi)$ Stop Wrong " "	(0) Stop " " "	$(-\sin\Phi)$ Stop Wrong " "	(+
7 	1.0 < 1. & > .5 .5 < .5	$(-2\sin\Phi)$ Stop Wrong " "	(0) Stop " " "	(0) Stop " " "	$(+2\sin\Phi)$ Stop Right " "	$(-\sin\Phi)$ Stop Wrong " "	(—
8 	1.0 < 1. & > .5 .5 < .5	$(+2\sin\Phi)$ Stop Right " "	(0) Stop " " "	(0) Stop " " "	$(-2\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	(
9 	1.0 < 1. & > .5 .5 < .5	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	(0) Stop " " "	
10 	1.0 < 1. & > .5 .5 < .5	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	(0) Stop " " "	
11 	1.0 < 1. & > .5 .5 < .5	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	(0) Stop " " "	
12 	1.0 < 1. & > .5 .5 < .5	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	(0) Stop " " "	

TABLE II

(f) se I correct " II " tage Lead 2 open.	(h) Phase I reversed " II correct Voltage Lead 1 open.	(i) Phase I reversed. " II correct. Voltage Lead 2 open.	(k) Phase I correct. " II reversed. Voltage Lead 1 open.	(l) Phase I correct. " II reversed. Voltage Lead 2 open.	(n) Phase I reversed. " II " Voltage Lead 1 open.	(o) Phase I reversed. " II " Voltage Lead 2 open.
$\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "
$\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "
$\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " ".	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "
$\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "
$(-\sin\Phi)$ Stop Wrong " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	$(+\sin\Phi)$ Stop Right " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "
$(+\sin\Phi)$ Stop Right " "	$(+\sin\Phi)$ Stop Right " "	$(+\sin\Phi)$ Stop Right " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	$(-\sin\Phi)$ Stop Wrong " "
$(-\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	$(+\sin\Phi)$ Stop Right " "	$(+\sin\Phi)$ Stop Right " "
$(+\sin\Phi)$ Stop Right " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	$(+\sin\Phi)$ Stop Right " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\sin\Phi)$ Stop Wrong " "
(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "
(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "
(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "
(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "

[KOUWENHOVEN]

NEW METHOD OF CHECKING CONNECTIONS

The method that the writer proposes for the checking of the correctness of the connections, is the interchange of voltage leads 1 and 2. Then if the original connections were correct, the rotation of the meter disk will cease at any value of the power factor (leading or lagging) on a balanced circuit. If the original connections were not correct, rotation in one direction or the other will take place after the interchange has been made. The proof of this is as follows:

Unity Power Factor. At unity power factor we find that for 12 cases the meter will run in the right direction with all the circuits intact. These are as follows: 1 (a), 2 (d), 3 (b), 4 (c), 9 (a), 9 (c), 10 (b), 10 (d), 11 (a), 11 (b), 12 (c) and 12 (d).

The effect of the interchange of voltage leads 1 and 2 is given in Table III. Table III and also Tables IV, V, VI and VII are derived from the values given in Table II. We note in Table III, that when the voltage leads 1 and 2 are interchanged, the rotation of the disk will cease for the four correct connections, and that in all of the other cases it will run in the wrong direction.

Power Factor <1.0 *and* >0.5 *lagging.* Under these conditions we find 20 cases where the meter will run in the right direction with all circuits intact. These are: 1 (a), 2 (d), 3 (b), 4 (c), 1 (c), 2 (b), 3 (d), 4 (a), 5 (c), 6 (b), 7 (d), 8 (a), 9 (a), 9 (c), 10 (b), 10 (d), 11 (a), 11 (b), 12 (c) and 12 (d).

The effect of the interchange of voltage connections on these cases is given in Table IV. From the table we see that, when the voltage connections are interchanged, the meter will stop for the four correct cases only, and for all other connections the meter will run either forward or backward.

Power Factor $= 0.5$ *Lagging.* At this power factor we find from Table II that there are 16 cases where the meter will run in the right direction. These are: 1 (a), 2 (d), 3 (b), 4 (c), 1 (c) 2 (b), 3 (d), 4 (a), 5 (c), 6 (b), 7 (d), 8 (a), 11(a), 11 (b), 12 (c) and 12 (d).

The effect that is produced by an interchange of the voltage leads 1 and 2 is given in Table V. We find after interchanging the leads that for each of the four correct connections the meter will stop, and that for any one of the other 12 cases the meter disk will rotate either right or wrong.

Power Factor <0.5 *Lagging.* For a power factor of less than 0.5 we see from Table II that there are 20 cases where the meter disk will run in the correct direction, with all connections intact. These are as follows: 1 (a), 2 (d), 3 (b), 4 (c), 1 (c), 2 (b), 3 (d),

TABLE III—POWER FACTOR = 1.0

Case	Voltage leads 1 and 2 interchanged gives case	Directon of Rotation of meter then becomes
1 (a)	5 (a)	Stop
2 (d)	6 (d)	"
3 (b)	7 (b)	"
4 (c)	8 (c)	"
9 (a)	10 (a)	Wrong
9 (c)	10 (c)	"
10 (b)	9 (b)	"
10 (d)	9 (d)	"
11 (a)	12 (a)	"
11 (b)	12 (b)	"
12 (c)	11 (c)	"
12 (d)	11 (d)	"

TABLE IV—POWER FACTOR < 1 AND > 0.5 LAGGING.

Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes	Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes
1 (a)	5 (a)	Stop	7 (d)	3 (d)	Right
2 (d)	6 (d)	"	8 (a)	4 (a)	"
3 (b)	7 (b)	"	9 (a)	10 (a)	Wrong
4 (c)	8 (c)	"	9 (c)	10 (c)	"
1 (c)	5 (c)	Right	10 (b)	9 (b)	"
2 (b)	6 (b)	"	10 (d)	9 (d)	"
3 (d)	7 (d)	"	11 (a)	12 (a)	"
4 (a)	8 (a)	"	11 (b)	12 (b)	"
5 (c)	1 (c)	"	12 (c)	11 (c)	"
6 (b)	2 (b)	"	12 (d)	11 (d)	"

TABLE V.
POWER FACTOR = 0.5 LAGGING.

Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes
1 (a)	5 (a)	Stop
2 (d)	6 (d)	"
3 (b)	7 (b)	"
4 (c)	8 (c)	"
1 (c)	5 (c)	Right
2 (b)	6 (b)	"
3 (d)	7 (d)	"
4 (a)	8 (a)	"
5 (c)	1 (c)	"
6 (b)	2 (b)	"
7 (d)	3 (d)	"
8 (a)	4 (a)	"
11 (a)	12 (a)	Wrong
11 (b)	12 (b)	"
12 (c)	11 (c)	"
12 (d)	11 (d)	"

4 (a), 5 (c), 6 (b), 7 (d), 8 (a), 9 (b), 9 (d), 10 (a), 10 (c), 11 (a), 11 (b), 12 (c) and 12 (d).

These cases are treated in Table VI, and it is evident that the rotation of the disk, as before, only ceases when the original connections were correct before the leads 1 and 2 were interchanged, and that for all other arrangements, rotation either forward or backward will take place.

Power Factor <1.0 *and* >0.5 *Leading.* We find from Table II

TABLE VI
POWER FACTOR < 0.5 LAGGING.

Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes	Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes
1 (a)	5 (a)	Stop	7 (d)	3 (d)	Right
2 (d)	6 (d)	"	8 (a)	4 (a)	"
3 (b)	7 (b)	"	9 (b)	10 (b)	Wrong
4 (c)	8 (c)	"	9 (d)	10 (d)	"
1 (c)	5 (c)	Right	10 (a)	9 (a)	"
2 (b)	6 (b)	"	10 (c)	9 (c)	"
3 (d)	7 (d)	"	11 (a)	12 (a)	"
4 (a)	8 (a)	"	11 (b)	12 (b)	"
5 (c)	1 (c)	"	12 (c)	11 (c)	"
6 (b)	2 (b)	"	12 (d)	11 (d)	"

TABLE VII
POWER FACTOR < 1.0 AND > 0.5 LEADING.

Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes	Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes
1 (a)	5 (a)	Stop	7 (a)	3 (a)	Right
2 (d)	6 (d)	"	8 (d)	4 (d)	"
3 (b)	7 (b)	"	9 (a)	10 (a)	Wrong
4 (c)	8 (c)	"	9 (c)	10 (c)	"
1 (b)	5 (b)	Right	10 (b)	9 (b)	"
2 (c)	6 (c)	"	10 (d)	9 (d)	"
3 (a)	7 (a)	"	11 (a)	12 (a)	"
4 (d)	8 (d)	"	11 (b)	12 (b)	"
5 (b)	1 (b)	"	12 (c)	11 (c)	"
6 (c)	2 (c)	"	12 (d)	11 (d)	"

that under these conditions there are 20 cases where the meter will run in the right direction, with all circuits intact. These are: 1 (a), 2 (d), 3 (b), 4 (c), 1 (b), 2 (c), 3 (a), 4 (d), 5 (b), 6 (c), 7 (a), 8 (d), 9 (a), 9 (c), 10 (b), 10 (d), 11 (a), 11 (b), 12 (c), and 12 (d).

The effect of interchanging leads 1 and 2 on these cases is treated in Table VII. It is clear from Table VII that the rotation of the disk, as for lagging values of the power factor, only ceases for the four correct connections when the interchange is made, and that for all other arrangements rotation either forward or backward will take place.

It may further be proved from Table II that for other values of leading power factor, an interchange of the voltage connections 1 and 2 will cause the rotation of the disk to cease for the four correct connections only.

It is evident from the above proof, that with a balanced load (motor load), the correctness of the connections of a polyphase watt-hour meter, provided with four voltage terminals, can be accurately checked at any power factor by the simple interchange of the voltage connections to the phases 1 and 2, when the meter is used without voltage transformers, and if the meter stops the original connections were correct.

The interchange may be easily and simply made at the meter terminals. The following set of rules for the identification of connections may be deduced from Tables II, III, IV, V, VI and VII.

1. If, after the interchange of voltage connections 1 and 2, the meter stops, then the original connections were correct.

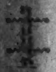
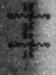
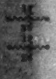
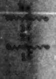
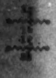
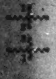
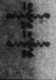
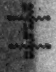
2. If, after the interchange of voltage connections 1 and 2, the meter continues to run in the right direction at increased speed, then the original connection was either 1 (c) or 2 (b) or 3 (d) or 4 (a), for leading currents 1 (b), 2 (c), 3 (a) or 4 (d), and the reversal of the connections of one of the current coils is all that is needed to rectify the mistake.

3. If, after the interchange the meter continues to run " right " but at greatly reduced speed (one-half its former speed) then the original was one of the arrangements of 5, 6, 7 or 8 and the voltage connections are now correct. The reversal of the proper current coil is all that is needed to make the connections correct.

4. If, after the interchange the meter runs in the wrong direction, then the original connection belonged to arrangements 9, 10, 11 or 12 and the entire system of connections must be carefully gone over and corrected.

The theoretical expressions for *P* for each of the 24 additional arrangements, mentioned above, are given in Tables VIII and IX. As stated, twelve of these arrangements are formed by connecting two meter terminals to phase 1, one to phase 2, and one to phase 3; and twelve by connecting two terminals to phase 2, one to phase 1, and one to phase 3. In Tables VIII and IX the

TA

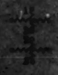
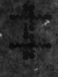
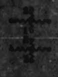
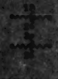
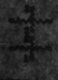
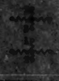
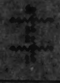
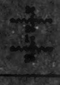
Arrangement	Power Factor	(a) Phase I correct. “ II “ Voltage Leads intact.	(b) Phase I reversed. “ II correct. Voltage Leads intact.	(c) Phase I correct. “ II reversed. Voltage Leads intact.	(d) Phase I reversed. “ II “ Voltage Leads intact.	(f) Phase I correct. “ II “ Voltage Lead 2 open.	Pha “ Volt
1 	1.0 $<$ 1. & $>$ .5 .5 $<$ .5	(0) Stop “ “ “	$(+\sqrt{3}\cos\Phi+\sin\Phi)$ Right “ “ “	$(-\sqrt{3}\cos\Phi-\sin\Phi)$ Wrong “ “ “	(0) Stop “ “ “	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong “ “ “	$(+\frac{1}{2}$
2 	1.0 $<$ 1. & $>$ .5 .5 $<$ .5	(0) Stop “ “ “	$(-\sqrt{3}\cos\Phi-\sin\Phi)$ Wrong “ “ “	$(+\sqrt{3}\cos\Phi+\sin\Phi)$ Right “ “ “	(0) Stop “ “ “	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right “ “ “	$(-\frac{1}{2}$
3 	1.0 $<$ 1. & $>$ .5 .5 $<$ .5	$(+\sqrt{3}\cos\Phi+\sin\Phi)$ Right “ “ “	(0) Stop “ “ “	(0) Stop “ “ “	$(-\sqrt{3}\cos\Phi-\sin\Phi)$ Wrong “ “ “	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right “ “ “	$(+\frac{1}{2}$
4 	1.0 $<$ 1. & $>$ .5 .5 $<$ .5	$(-\sqrt{3}\cos\Phi-\sin\Phi)$ Wrong “ “ “	(0) Stop “ “ “	(0) Stop “ “ “	$(+\sqrt{3}\cos\Phi+\sin\Phi)$ Right “ “ “	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong “ “ “	$(-\frac{1}{2}$
5 	1.0 $<$ 1. & $>$ .5 .5 $<$ .5	$(-\frac{1}{2}\sqrt{3}\cos\Phi+1.5\sin\Phi)$ Wrong — Right “	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right “ “ “	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong “ “ “	$(+\frac{1}{2}\sqrt{3}\cos\Phi-1.5\sin\Phi)$ Right — Wrong “	$(+\sin\Phi)$ Stop Right “ “	$(-\frac{1}{2}$
6 	1.0 $<$ 1. & $>$ .5 .5 $<$ .5	$(+\frac{1}{2}\sqrt{3}\cos\Phi-1.5\sin\Phi)$ Right — Wrong “	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong “ “ “	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right “ “ “	$(-\frac{1}{2}\sqrt{3}\cos\Phi+1.5\sin\Phi)$ Wrong — Right “	$(-\sin\Phi)$ Stop Wrong “ “	$(+\frac{1}{2}$
7 	1.0 $<$ 1. & $>$ .5 .5 $<$ .5	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right “ “ “	$(-\frac{1}{2}\sqrt{3}\cos\Phi+1.5\sin\Phi)$ Wrong — Right “	$(+\frac{1}{2}\sqrt{3}\cos\Phi-1.5\sin\Phi)$ Right — Wrong “	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong “ “ “	$(+\sin\Phi)$ Stop Right “ “	$(+\frac{1}{2}$
8 	1.0 $<$ 1. & $>$ .5 .5 $<$ .5	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong “ “ “	$(+\frac{1}{2}\sqrt{3}\cos\Phi-1.5\sin\Phi)$ Right — Wrong “	$(-\frac{1}{2}\sqrt{3}\cos\Phi+1.5\sin\Phi)$ Wrong — Right “	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right “ “ “	$(-\sin\Phi)$ Stop Wrong “ “	$(-\frac{1}{2}$

VIII

rrect. " d 3 open.	(i) Phase I reversed. " II correct. Voltage Lead 2 open.	(j) Phase I reversed " II correct. Voltage Lead 3 open.	(l) Phase I correct. " II reversed. Voltage Lead 2 open.	(m) Phase I correct. " II reversed. Voltage Lead 3 open.	(o) Phase I reversed. " II " Voltage Lead 2 open.	(p) Phase I reversed. " II " Voltage Lead 3 open.
$\Phi + \frac{1}{2}\sin\Phi)$ ht	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "
$\Phi - \frac{1}{2}\sin\Phi)$ ng	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "
$\Phi + \frac{1}{2}\sin\Phi)$ ht	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "
$\Phi - \frac{1}{2}\sin\Phi)$ ng	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "
$\Phi + \frac{1}{2}\sin\Phi)$ ng p ht	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\sin\Phi)$ Stop Wrong " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong
$\Phi - \frac{1}{2}\sin\Phi)$ ht p ng	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right
$\Phi - \frac{1}{2}\sin\Phi)$ ht p ng	$(+\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\sin\Phi)$ Stop Wrong " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right
$\Phi + \frac{1}{2}\sin\Phi)$ ng p ht	$(-\sin\Phi)$ Stop Wrong " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong

[KOUWENHOVEN]

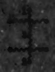
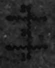
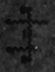
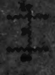
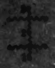
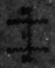
TABLE

Arrangement	Power factor	(a) Phase I correct. " II " Voltage Leads intact.	(b) Phase I reversed. " II correct. Voltage Leads intact.	(c) Phase I correct. " II reversed. Voltage Leads intact.	(d) Phase I reversed. " II " Voltage Leads intact.	(e) Phase I correct. " II " Voltage Lead 1 open.	(g) Phase I corre " II Voltage Lead
1 	1.0 < 1. & > .5 .5 < .5	(0) Stop " " "	$(-\sqrt{3}\cos\Phi+\sin\Phi)$ Wrong " Stop Right	$(+\sqrt{3}\cos\Phi-\sin\Phi)$ Right " Stop Wrong	(0) Stop " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi-$ Right " Stop Wrong
2 	1.0 <1. & > .5 .5 < .5	(0) Stop " " "	$(+\sqrt{3}\cos\Phi-\sin\Phi)$ Right " Stop Wrong	$(-\sqrt{3}\cos\Phi+\sin\Phi)$ Wrong " Stop Right	(0) Stop " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi+$ Wrong " Stop Right
3 	1.0 < 1. & > .5 .5 < .5	$(-\sqrt{3}\cos\Phi+\sin\Phi)$ Wrong " Stop Right	(0) Stop " " "	(0) Stop " " "	$(+\sqrt{3}\cos\Phi-\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi+$ Wrong " Stop Right
4 	1.0 < 1. & > .5 .5 < .5	$(+\sqrt{3}\cos\Phi-\sin\Phi)$ Right " Stop Wrong	(0) Stop " " "	(0) Stop " " "	$(-\sqrt{3}\cos\Phi+\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi-$ Right " Stop Wrong
5 	1.0 <1. & > .5 .5 <.5	$(-\frac{1}{2}\sqrt{3}\cos\Phi-1.5\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi+1.5\sin\Phi)$ Right " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-$ Wrong " " "
6 	1.0 < 1. & > .5 .5 < .5	$(+\frac{1}{2}\sqrt{3}\cos\Phi+1.5\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi-1.5\sin\Phi)$ Wrong " " "	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+$ Right " " "
7 	1.0 < 1. & > .5 .5 < .5	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi-1.5\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+1.5\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-$ Wrong " " "
8 	1.0 < 1. & > .5 .5 < .5	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi+1.5\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-1.5\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\sin\Phi)$ Stop Wrong " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+$ Right " " "

E IX

) rrect. " ad 3 open.	(h) Phase I reversed. " II correct. Voltage Lead 1 open.	(j) Phase I reversed. " II correct. Voltage Lead 3 open.	(k) Phase I correct. " II reversed. Voltage Lead 1 open.	(m) Phase I correct. " II reversed. Voltage Lead 3 open.	(n) Phase I reversed. " II " Voltage Lead 1 open.	(p) Phase I reversed. " II " Voltage Lead 3 open.
$\Phi - \frac{1}{2}\sin\Phi)$ ht p ng	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right
$\Phi + \frac{1}{2}\sin\Phi)$ ng p ht	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong
$\Phi + \frac{1}{2}\sin\Phi)$ ng p ht	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong
$\Phi - \frac{1}{2}\sin\Phi)$ ht p ng	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Wrong " Stop Right
$\Phi - \frac{1}{2}\sin\Phi)$ ng	$(+\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "
$+ \frac{1}{2}\sin\Phi)$ t	$(-\sin\Phi)$ Stop Wrong " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(+\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "
$- \frac{1}{2}\sin\Phi)$ g	$(+\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "
$+ \frac{1}{2}\sin\Phi)$ t	$(-\sin\Phi)$ Stop Wrong " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi + \frac{1}{2}\sin\Phi)$ Right " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi - \frac{1}{2}\sin\Phi)$ Wrong " " "

[Kouwenhoven.]

Arrangement	Power Factor	(a) Phase I correct. " II " Voltage Leads intact.	(b) Phase I reversed. " II correct Voltage Leads intact.	(c) Phase I correct. " II reversed. Voltage Leads intact.	(d) Phase I reversed. " II " Voltage Leads intact.	(e) Phase I correct. " II " Voltage Lead 1 open.	(f) Phase I correct. " II " Voltage Lead 2 ope
1 	1.0 < 1. & > .5 .5 < .5	$(+\sqrt{3}\cos\Phi)$ Right " " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	* $(-\sqrt{3}\cos\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}$ si Right " " "
2 	1.0 < .1 & > .5 .5 < .5	(0) Stop " " "	$(-2\sin\Phi)$ Stop Wrong " "	$(+2\sin\Phi)$ Stop Right " "	(0) Stop " " "	$(+\sin\Phi)$ Stop Right " "	$(-\sin\Phi)$ Stop Wrong " "
3 	1.0 < .1 & > .5 .5 < .5	(0) Stop " " "	$(+\sqrt{3}\cos\Phi+\sin\Phi)$ Right " " "	$(-\sqrt{3}\cos\Phi-\sin\Phi)$ Wrong " " "	(0) Stop " " "	$(+\frac{1}{4}\sqrt{3}\cos\Phi-\frac{3}{4}\sin\Phi)$ Right Wrong "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}$ si Wrong " " "
4 	1.0 < 1. & > .5 .5 < .5	(0) Stop " " "	$(-\sqrt{3}\cos\Phi+\sin\Phi)$ Wrong " Stop Right	$(+\sqrt{3}\cos\Phi-\sin\Phi)$ Right " Stop Wrong	(0) Stop " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{4}\sqrt{3}\cos\Phi+\frac{3}{4}$ si Right " " "
5 	1.0 < 1. & > .5 .5 < .5	$(-\frac{1}{2}\sqrt{3}\cos\Phi-1.5\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi+1.5\sin\Phi)$ Right " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{4}\sqrt{3}\cos\Phi-\frac{3}{4}$ si Wrong " " "
6 	1.0 < 1. & > .5 .5 < .5	$(-\frac{1}{2}\sqrt{3}\cos\Phi+1.5\sin\Phi)$ Wrong Right "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-1.5\sin\Phi)$ Right Wrong "	$(-\frac{1}{4}\sqrt{3}\cos\Phi+\frac{3}{4}\sin\Phi)$ Wrong Right "	$(+\sin\Phi)$ Stop Right " "

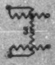
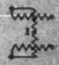
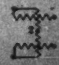
Arrangement	Power Factor	(a) Phase I correct. " II " Voltage Leads intact.	(b) Phase I reve " II corr Voltage Lead
1 	1.0 < 1. & > .5 .5 < .5	$(+\sqrt{3}\cos\Phi)$ Right " " "	(— sin Stop Wron " "
2 	1.0 < 1. & > .5 .5 < .5	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi$ Right " " "
3 	1.0 < 1. & > .5 .5 < .5	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi$ Wron " Stop Righ

TABLE X

open.	(g) Phase I correct. " II " Voltage Lead 3 open.	(h) Phase I reversed. " II correct. Voltage Lead 1 open.	(i) Phase I reversed. " II correct. Voltage Lead 2 open.	(j) Phase I reversed. " II correct. Voltage Lead 3 open.	(k) Phase I correct. " II reversed. Voltage Lead 1 open.	(l) Phase I correct. " II reversed. Voltage Lead 2 open.	(m) Phase I correct. " II reversed. Voltage Lead 3 o
$\frac{1}{2}\sin\Phi)$	$(+\frac{1}{2}\sqrt{3}\cos\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sin\Phi)$ Stop Wrong " "
	$(-\frac{1}{2}\sqrt{3}\cos\Phi)$ Wrong " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sin\Phi)$ Stop Right " "
$\frac{1}{2}\sin\Phi)$	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}$ Wrong " " "
$\frac{1}{2}\sin\Phi)$	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}$ Right " Stop Wrong
$\frac{1}{2}\sin\Phi)$	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}$ Right " " "
	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}$ Wrong " Stop Right

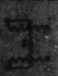
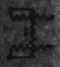
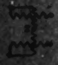
TABLE XI

b) reversed. correct. eads intact.	(c) Phase I correct. " II reversed Voltage Leads intact.	(d) Phase I reversed. " II " Voltage Leads intact.	(g) Phase I correct. " II " Voltage Lead open.	(j) Phase I reversed. " II correct. Voltage Lead open.	(m) Phase I correct. " II reversed. Voltage Lead open.	(p) Phase I reversed. " II " Voltage Lead open.
$\sin\Phi)$ top rong " "	$(+\sin\Phi)$ Stop Right " "	$(-\sqrt{3}\cos\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi)$ Right " " "	$(+\frac{1}{2}\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi)$ Wrong " " "
os $\Phi+\frac{1}{2}\sin\Phi)$ ight " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "
os $\Phi+\frac{1}{2}\sin\Phi)$ rong " Stop ight	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "	(0) Stop " " "

TABLE X

(c) Phase I correct. " II reversed. Voltage Leads intact.	(d) Phase I reversed. " II " Voltage Leads intact.	(e) Phase I correct. " II " Voltage Lead 1 open.	(f) Phase I correct. " II " Voltage Lead 2 open.	(g) Phase I correct. " II " Voltage Lead 3 open.	(h) Phase I reversed. " II correct. Voltage Lead 1 open.	(i) Phase I reversed. " II correct. Voltage Lead 2 open.	Phase " Voltag
$(+\sin\Phi)$ Stop Right " "	$(-\sqrt{3}\cos\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	(+
$(+2\sin\Phi)$ Stop Right " "	(0) Stop " " "	$(+\sin\Phi)$ Stop Right " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi)$ Wrong " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\sin\Phi)$ Stop Wrong " "	(−
$(-\sqrt{3}\cos\Phi-\sin\Phi)$ Wrong " " "	(0) Stop " " "	$(+\frac{1}{4}\sqrt{3}\cos\Phi-\frac{3}{4}\sin\Phi)$ Right ——— Wrong "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{4}\sqrt{3}\cos\Phi+\frac{1}{4}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	(+ ½ √3
$(+\sqrt{3}\cos\Phi-\sin\Phi)$ Right " Stop Wrong	(0) Stop " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{4}\sqrt{3}\cos\Phi+\frac{3}{4}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{4}\sqrt{3}\cos\Phi+\frac{1}{4}\sin\Phi)$ Wrong " Stop Right	(− ½ √3
$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi+1.5\sin\Phi)$ Right " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{4}\sqrt{3}\cos\Phi-\frac{3}{4}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{4}\sqrt{3}\cos\Phi-\frac{1}{4}\sin\Phi)$ Right " Stop Wrong	(− ½ √3
$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-1.5\sin\Phi)$ Right ——— Wrong "	$(-\frac{1}{4}\sqrt{3}\cos\Phi+\frac{3}{4}\sin\Phi)$ Wrong ——— Right "	$(+\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{4}\sqrt{3}\cos\Phi-\frac{1}{4}\sin\Phi)$ Wrong " " "	$(+\sin\Phi)$ Stop Right " "	(+ ½ √3

TABLE XI

Arrangement	Power Factor	(a) Phase I correct. " II " Voltage Leads intact.	(b) Phase I reversed. " II correct. Voltage Leads intact.	(c) Phase I correct. " II reversed Voltage Leads intact.	(d) Phase I reversed. " II " Voltage Leads intact.	(g) Phase I correct. " II " Voltage Lead open.
1 	1.0 < 1. & > .5 .5 < .5	$(+\sqrt{3}\cos\Phi)$ Right " " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	$(-\sqrt{3}\cos\Phi)$ Wrong " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi)$ Right " " "
2 	1.0 < 1. & > .5 .5 < .5	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	(0) Stop " " "
3 	1.0 < 1. & > 5 .5 < .5	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	(0) Stop " " "

(j) ase I reversed. " II correct. ltage Lead 3 open.	(k) Phase I correct. " II reversed. Voltage Lead 1 open.	(l) Phase I correct. " II reversed. Voltage Lead 2 open.	(m) Phase I correct. " II reversed. Voltage Lead 3 open.	(n) Phase I reversed. " II " Voltage Lead 1 open.	(o) Phase I reversed. " II " Voltage Lead 2 open.	(p) Phase I reversed. " II " Voltage Lead 3 open.
$(+\frac{1}{2}\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{2}\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi)$ Wrong " " "
$(-\frac{1}{2}\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sin\Phi)$ Stop Right " "	$(-\sin\Phi)$ Stop Wrong " "	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi)$ Right " " "
$\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{4}\sqrt{3}\cos\Phi-\frac{1}{4}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\frac{1}{4}\sqrt{3}\cos\Phi+\frac{1}{4}\sin\Phi)$ Wrong ——— Right "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(-\frac{1}{4}\sqrt{3}\cos\Phi-\frac{1}{4}\sin\Phi)$ Wrong " " "
$\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{4}\sqrt{3}\cos\Phi-\frac{1}{4}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(-\frac{1}{4}\sqrt{3}\cos\Phi-\frac{1}{4}\sin\Phi)$ Wrong " " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right
$\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Wrong " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{4}\sqrt{3}\cos\Phi+\frac{1}{4}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "	$(+\sin\Phi)$ Stop Right " "	$(+\frac{1}{4}\sqrt{3}\cos\Phi+\frac{1}{4}\sin\Phi)$ Right " " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Right " " "
$\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong	$(+\frac{1}{4}\sqrt{3}\cos\Phi+\frac{1}{4}\sin\Phi)$ Right " " "	$(-\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$ Wrong " Stop Right	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right ——— Wrong "	$(-\sin\Phi)$ Stop Wrong " "	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$ Right " Stop Wrong

[KOUWENHOVEN]

(j) Phase I reversed. " II correct. Voltage Lead open.	(m) Phase I correct. " II reversed. Voltage Lead open.	(p) Phase I reversed. " II " Voltage Lead open.
$(+\frac{1}{2}\sin\Phi)$ Stop Right " "	$(-\frac{1}{2}\sin\Phi)$ Stop Wrong " "	$(-\frac{1}{2}\sqrt{3}\cos\Phi)$ Wrong " " "
(0) Stop " " "	(0) Stop " " "	(0) Stop " " "
(0) Stop " " "	(0) Stop " " "	(0) Stop " " "

unimportant arrangements similar to arrangements 9, 10, 11 and 12 of Fig. 2 have been omitted. The expressions for these unimportant arrangements may be found elsewhere if needed. For example, consider arrangement 9 of Table VIII. Arrangement 9, Table VIII, is made by connecting the voltage terminals of meter element I to phases 2 and 3, and by connecting both voltage terminals of meter element II to phase 1. The theoretical expressions for the resulting cases are to be found in Table II, arrangement 5, cases (e), (h), (k) and (n).

CHECKING THE CONNECTIONS

The elimination of the incorrect connections treated in Tables VIII and IX is accomplished by the interchange of voltage leads 1 and 2. If the wiring is open the interchange is made at the meter terminals, and in places where the wires to the meter run in conduit the interchange is made at the line. In either case the inspection of the connections incidental to making the interchange indicates at once the mistake, as it is apparent that two of the voltage terminals are connected to one of the phases that supply the current coils of the meter with current. The correction of the mistake is simple.

CLASS A METERS WITH VOLTAGE TRANSFORMERS

The addition of voltage transformers complicates the connections, and makes possible a large number of additional connections. That this is a fact is clearly seen when one considers that the twelve arrangements of connections shown in Fig. 2 may be applied to the primary side of the transformers, and that for each one of these there are 24 different possible arrangements of the connections between the four secondary terminals of the transformers and the four voltage terminals of the polyphase meter.

Four of these arrangements are shown in Fig. 5. However, it is evident that the four arrangements shown in Fig. 5 are electrically the same. A careful study of the conditions shows that no new electrical arrangements of the circuits are introduced by a combination of any one of the first eight cases applied to the primary side of the transformers with any one of the first eight arrangements between the secondaries of the transformers and the meter. The same is also true when any one of the last four cases on the primary side is combined with any one of the same cases on the secondary side. However, any combination made with any one of the first eight arrangements on the primary side, with any one of the last four on the secondary side of the transformers, introduces new cases. In all of these new cases which are brought about by the addition of the voltage transformers, the two secondary windings of the transformers and the two voltage coils of the polyphase meters are in series. Two of these cases are illustrated in Fig. 6.

For any one of these added cases formulas for the rate and direction of rotation can be derived if necessary. These cases are not only very improbable, but a reversal of the voltage leads 1 and 2 on the primary sides of the transformers will in no case cause the meter to stop. Therefore, the use of voltage transformers does not introduce any new cases of importance, and the expressions given in Tables II, VIII and IX apply to this type of meter when used with transformers.

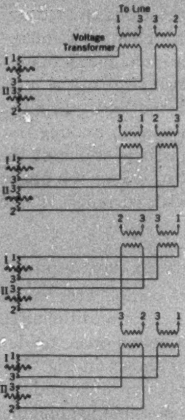


FIG. 5

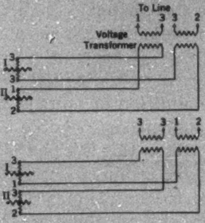


FIG. 6

Since the same expressions for *P* hold good, irrespective of the presence or absence of voltage transformers, the same mode of checking the connections is applicable in both cases. Therefore, the correct connections of a polyphase watt-hour meter, provided with four separate voltage terminals, when used with voltage transformers, may be checked by the interchange of voltage connections 1 and 2 on the primary side of the voltage transformers. And if the connections were originally correct, and the load is balanced, the meter will stop at any power factor. Further, if we assume that all of the improbable connections of cases 9, 10, 11 and 12 of Table II are absent, and that all incorrect connections illustrated in Tables VIII and IX will be eliminated by the inspection of the connections incidental to making the interchange, then we may apply rules 1, 2 and 3 for the correction of mistakes in the connections.

CLASS B METERS

The correct connections of Class B type of polyphase meter are shown in Fig. 7. With this class of meter the presence of voltage transformers does not introduce any new cases, and therefore the following discussion applies equally well to meters of this type when used either with or without voltage transformers.

The number of possible arrangements of the voltage connections to the three meter terminals is found to be six. These are shown in Fig. 8. As in the case of Class A meters, each arrangement of the voltage connections has four different arrangements of the current coils, and each arrangement of the connections of the current coils has four conditions of operation, depending upon whether all the voltage connections are intact or if one of them is open. Therefore, we find a total of 96 different connections or cases.

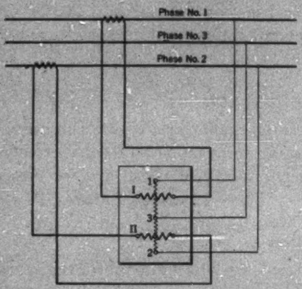


FIG. 7

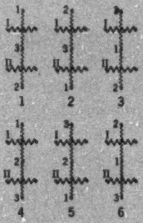


FIG. 8

The theoretical expressions for P were derived for each one of the cases, and these are to be found in Table X. With this type of meter, the opening of the voltage connection 3 does not give a case analogous to those due to the opening of either leads 1 or 2, but a separate and distinct case. The following example will serve to illustrate the derivation of the value of P for these cases:

Case 1 (g) *Phase I and Phase II Correct, Voltage Lead* 3 *Open.*

The vector diagram is given in Fig. 9. The voltage is divided between the two potential coils of the meter, and therefore, half of the voltage is across each coil and we find that

$$P = \frac{1}{2} I_1 E_{1,2} \cos (30 + \Phi) + \frac{1}{2} I_2 E_{2,1} \cos (30 - \Phi)$$

$$P = \left(+ \frac{\sqrt{3}}{2} \cos \Phi \right) I E$$

The correctness of each of the 96 expressions was checked experimentally as in the case of the Class A type of meter. Table X not only gives the expressions but also the directions of rotation of the meter disk at several different values of lagging power factor.

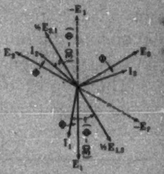


FIG. 9

CHECKING OF CONNECTIONS

From Table X we find that there are 60 cases where the meter will run in the correct direction at some power factor between unity and zero lagging, however, only 12 of these are for cases where all the circuits are intact. These 12 are as follows: 1 (a), 1 (c), 2 (c), 3 (b), 4 (b), 4 (c), 5 (b), 5 (c), 5 (d), 6 (a), 6 (b) and 6 (d).

Of these 12 cases there is only one case where the meter registers correctly under all conditions the amount of power consumed, and that is case 1 (a). A careful study of the table does not reveal any simple method of checking the correctness of the connections 1 (a) that does not apply equally well to some of the incorrect cases. The arrangements of connections that do not offer any simple means of elimination are cases 5 (d), 6 (a) and 6 (d). However, mistakes that are illustrated by cases coming under 3, 4, 5 and 6 are not often made, especially if the common voltage terminal of the meter to which phase 3 is connected is plainly marked. If this terminal is marked, it is practically impossible to make any mistake in its connection to the proper phase, and therefore, we need only consider cases coming under arrangements 1 and 2.

Under arrangements 1 and 2 of the voltage connections we find only three cases where the meter will run in the right direction. These are: 1 (a), 1 (c) and 2 (c). In addition to the check of the correctness of the connections produced by the opening of the voltage supply to each element of the meter in turn, there is also a check that is sometimes employed with this class of meter which consists in opening lead 3.

The same criticism, namely, that it cannot be relied upon, that applied to the check obtained by opening the voltage supply of each element in turn, as applied to the Class A type of meter, applies equally well when used with this class of meters. When we study the effect of opening lead 3, we see from Table VIII that when we open lead 3 for case 1 (a) we get case 1 (g), and the meter continues to run in the right direction at exactly one-half speed. For case 1 (c) we get 1 (m) and the meter now runs in the wrong direction, and for case 2 (c) we get 2 (m), and the meter continues to run in the right direction at exactly one-fourth its former speed. Therefore, this check may be relied upon provided the load remains constant.

CHECK PRODUCED BY THE INTERCHANGE OF THE VOLTAGE CONNECTIONS TO PHASES 1 AND 2

l. 35
16

At unity power factor we have only case 1 (a) possible and an interchanging of the voltage leads 1 and 2 will give case 2 (a) and the rotation of the disk will cease. This is also true of case 1 (a) for any value of the power factor either leading or lagging.

At all values of lagging power factor below unity, we may have in addition to case 1 (a) either 1 (c) or 2 (c). The interchange for voltage leads for the case 1 (c) gives case 2 (c) and the meter continues to run in the right direction at double its original speed. The interchange for case 2 (c) gives 1 (c) and the meter continues to run in the right direction at one-half its original speed.

For leading values of the power factor we find three cases where the meter disk will rotate in the right direction. These are: 1 (a), 1 (b) and 2 (b). In cases 1 (b) and 2 (b) the disk will continue to rotate in the right direction after the interchange is made.

It is evident from the above, that the interchange of the voltage leads 1 and 2 will serve to eliminate all incorrect connections and check the proper connections for Class B meters, if we allow the assumption that the common voltage terminal is connected to its proper phase, *i. e.*, to the phase that does not supply current to the current coils of the meter. This connection is very simple if the terminal is clearly marked. Rules 1 and 2 also apply to this meter, and aid in the correction of mistakes. The interchange of leads 1 and 2 may always be made at the terminals of the instrument.

CLASS C METERS

The correct connections of the Class C type of meter are shown in Fig. 10. Instrument transformers are seldom used with this type of meter, which is essentially a house meter. The three possible arrangements of the voltage connections are illustrated in Fig. 11.

The expressions for P and the direction of rotation at different power factors are given in Table XI.

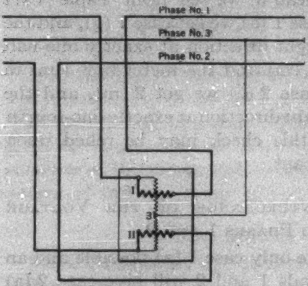


FIG. 10

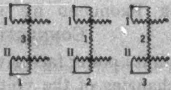


FIG. 11

CHECKING THE CONNECTIONS

Table XI shows that there are 8 cases where the meter will run in the right direction at some value of the power factor, when all its circuits are intact. Of these 8 cases, case 1 (a) is the only case or arrangement of connections where the meter will operate correctly under all conditions. The 8 cases are: 1 (a), 1 (c), 2 (a), 2 (b), 3 (a), 3 (b), 3 (c) and 3 (d).

The check for this class of meters consists in opening the single voltage connections to the meter*; for case 1 (a) this gives 1 (g) and the meter continues to run in the right direction at one-half its former speed.

The opening of the voltage connection for case 1 (c) gives case 1 (m) and the meter stops or runs in the wrong direction, depending on the power factor. The opening of the voltage connections for any one of the remaining cases causes the meter to stop under all conditions. It may be stated that a balanced load is not essential for making the test.

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* *Electrical World*, Vol. 63, p. 144, 1914.

OPENING THE SUPPLY AS A METHOD OF CHECKING THE CONNECTIONS

In addition to the above-mentioned checks there is a test of the correctness of the connections that may be applied where it is permissible to open one phase at a time of the supply without interrupting the load. A phase must be opened in two places at the same time, namely, between the meter and the supply line and between the meter and the load.

This test is as follows: Assume that the meter is connected in a three-phase circuit, where one of the phases may be opened without interrupting the load. Now, with the meter running in the right direction, open one of the phases that supplies current to one of the current coils of the meter as directed above. The meter should continue to rotate in the right direction if the connections are correct; because it is now operating as a single-phase meter, registering the power supplied to a single-phase load. Replace the fuses and open the phase that supplies current to the other current coil of the meter. The meter should continue to rotate in the right direction for the same reason as before. If the meter stops or if its direction of rotation changes when either line is open, then the connections are incorrect and must be carefully traced out and the mistake rectified. In making this test it is not necessary to know the power factor of the load nor is a balanced load necessary.

Each phase that supplies current to the meter must be opened in two places during this test. If only a single opening is made between the meter and the load, both voltage coils of the meter will still be excited, and we may have such incorrect connections as cases 5 (c) 5 (b), 7(d), 8 (a) of Table II or 2 (c) of Table X which also give rotation in the right direction with either line open. If a single opening is made between the meter and the supply line and if the load consists of an induction motor or other similar apparatus, both voltage coils will still be excited due to the voltages induced in the motor windings, and we may have incorrect connections as above. Therefore, it is necessary to open the same phase of the circuit in two places simultaneously.

EXAMPLE OF THE APPLICATION OF THE NEW METHOD

The following is an example of the application of the method of checking the correctness of a polyphase watt-hour meter on a three-phase circuit by means of the interchange of voltage connections to phases 1 and 2. For this example the writer has assumed that we have to install a polyphase watt-hour meter with four voltage and four current terminals on a circuit requiring the use of voltage and current transformers. While making the test, the load on the circuit must be balanced and may consist of a three-phase induction motor, a three-phase bank of transformers or other similar apparatus. As it is difficult to obtain a balanced load with lamps, the lighting circuits should be open.

Connect the meter according to the diagram of connections (see Fig. 12) so that it rotates in the right direction.

Having obtained rotation in the right direction, interchange the connections on the primary side of the potential transformers to phases 1 and 2, and if rotation ceases the original connections were correct, and should be restored.

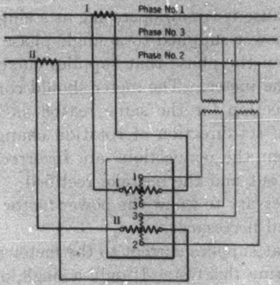

Fig. 12

If after making the interchange, the meter continues to run in the right direction but at increased speed, the original connections were correct, but the connections of one of the current coils were reversed. Restore the voltage connections to their original condition and reverse the connections of the current coil that will give rotation in the right direction after reversal.

If, after making the interchange, the meter continues to run in the right direction, but at reduced speed, the voltage connections are now correct, and one current coil is reversed. Reverse the connections of the current coil that will give rotation in the right direction after reversal.

Having satisfied the conditions of the test, the voltage terminals of the meter that are at the same potential may be connected together and grounded if desired.

SUMMARY AND CONCLUSIONS

The results of the investigation show clearly, first: That the check upon the correctness of the connections made by opening the current or voltage supply to each element in turn, is unreliable and may lead to erroneous results. Furthermore, a knowledge of the power factor is essential to its use.

Second: That the check upon the correctness of the connections made by opening the voltage connections to the phase that does not supply current to the two single-phase elements of the meter is only accurate in case of meters of Class C or to meters similarly connected.

Third: That the check upon the correctness of the connections made by opening in turn each of the three-phase lines that supply current to the current coils of the meter, is accurate at any power factor and on balanced or unbalanced load; provided the opening is made between the meter and the supply line.

Fourth: That the check upon the correctness of the connections made by the interchange of voltage connections to phases 1 and 2 is accurate at any power factor on a balanced load for Class B meters, if we make the assumption that phase 3 is connected to the proper terminal and that if the original connections were correct the meter stops. This also applies to meters having four voltage terminals when two of these are connected together, and from a common terminal.

Fifth: That the check upon the correctness of the connections made by the interchange of voltage leads 1 and 2 is accurate at any power factor on a balanced circuit for Class A meters, and that if the original connections were correct the meter stops.

Sixth: That in case the connections are incorrect for Class A and B meters, the interchange of leads 1 and 2 gives the necessary information for correcting the mistake (see Rules 2 and 3, page 172).

The investigation also shows that there is a simple means of ascertaining the power factor on a three-phase circuit where a polyphase watt-hour meter is installed. This method may be used with any type of meter. It is as follows: Note the time of one revolution of the disk when the meter is connected correctly and registering the given load. Then reverse the connections of either current coil, and note the time of one revolution, with the given load. Then

$$\tan \Phi = \frac{\sqrt{3}\,(\text{Time of one revolution, meter connected correctly})}{\text{Time of one revolution with one current coil reversed}}$$

The experimental work connected with this investigation was carried on in the new electrical laboratories of the Johns Hopkins University. The writer wishes to thank Mr. J. R. Cruikshank, Dr. J. B. Whitehead, Mr. F. V. Magalhaes and Mr. W. S. Brown for their kindness and assistance.

BIBLIOGRAPHY

PROCEEDINGS A. I. E. E. Vol. 27, p. 801, 198.
Bulletin Schweiz. Elek. Verein, Vol. 5, p. 270, 1914.
Electrical World, Vol. 59, p. 1310, 1912.
Electrical World, Vol. 63, p. 144-145, 1914.
Electrical Journal, Vol. 4, p. 89, 1907.
Electric Journal, Vol. 5, p. 290, 1908.
Electric Journal, Vol. 9, p. 765, 1912.
Elektrotech. Zeitschrift, Vol. 34, p. 1482, 1913.
General Electric Review, p. 350, 1912.
Hand Book, National Electric Light Association, p. 420
Elektrotech. & Maschinenbau, March 18, 1906.
Electrical World, Vol. 54, p. 1109, 1909.
L'Eclairage Elec. April 15, 1905.

DISCUSSION ON "A METHOD OF DETERMINING THE CORRECTNESS OF POLYPHASE WATTMETER CONNECTIONS" (KOUWENHOVEN), NEW YORK, FEB. 9, 1916.

W. H. Pratt: The author has made a very large amount of painstaking effort in collecting and analyzing the behavior of the meters with these miscellaneous connections. There is one point that is emphasized throughout the paper, that this checking must be made under balanced load conditions except in one particular case. There should be a great deal of care exercised in deciding whether you have a balanced condition in applying the check. The fact that you use a motor which tends to take a balanced load does not necessarily mean that the load will be balanced unless the voltages are strictly balanced. A very small unbalancing of voltage may mean a very large amount of unbalancing in the power station. This point emphasizes the fact that you should always be very particular in following the diagrams of connections. It is a very easy matter to systematically arrange most work so that you can follow the diagrams just as if you had a column of figures to add, and then very carefully do the work. There is a temptation, however, to rely on the check, but a check should be made bearing in mind that you have limitations which might seriously affect the conclusions.

Again, if you find that you have trouble it may be a very difficult matter to locate the cause of it. I have in mind a case which was called to my attention not many months ago in which all ordinary checks applied indicated that the connections were correctly made, even to tracing out the wiring, but there was evidence of something seriously wrong. When we came to trace it down, it appeared that there were two sets of instruments on the switchboard, the switchboard being in two parts, and the connection that was supposed to be a ground connection, simply served as a common zero potential connection. The two parts of the board were each individually connected up all right, but it so happened that the instruments on one portion required to have a common connection with the instruments on another portion, and this common connection was omitted, and there was a most mystifying behavior of the apparatus.

The author says that meters which he designates as class C meters cannot be used with either voltage or current transformers. Of course, it is quite possible to use such meters by making interconnections of the circuit, and making a simple interconnected secondary network.

Again, the remark is made: "By the use of the table it is also possible in cases where incorrect or open connections are found, to determine from the meter readings, when the conditions of the circuit are known, the actual kw-hr. that have been used." I think the expression of the author "when the conditions of the circuit are known" should be very much emphasized, because ordinarily the conditions of the circuit are such that the loads are not of definite power factor, and unless that is true throughout the whole period of operations, no conclusions could be drawn.

G. A. Sawin: The author's methods of making his calculations are the same that I have followed for some years, but I have laid out my diagram a little differently. For example suppose we find a meter connected in a certain manner Fig. 1 and desire to know its accuracy; we make a diagram, Fig. 2. We find the current coil of element *A* is in line 1, and the current coil of element *B* is in line 3. The potential of element *A* is connected from 1-2 and of element *B* from 3-1 as shown. I have shown an incorrect connection for the purpose of illustration. Now we must always remember that the meter records exactly what it received, no matter whether it is the true power or not. In other words, if we treat each element in this case as a single-phase meter, and remember the measured power equals the voltage received times the current received, times the cosine of the angle of lag between this particular current and potential, we will immediately see what each element is measuring. Add the results of the two elements together, and we will have the total measured power. Compare this result to the true power, and the correct answer is obtained. In this case the measured power is $EI\cos(30^\circ + a) + EI\cos(30^\circ + a) = 2EI\cos(30^\circ + a)$.

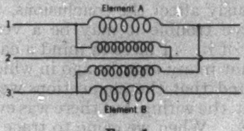

FIG. 1

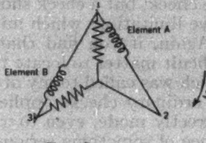

FIG. 2

The diagram to me personally is clearer, and shows exactly how to arrive at correct results in any case.

Mr. Pratt has called attention to the fact that in applying the author's method, we must have a balanced load. If we have an unbalanced load the results will not always come out, as expected. We often find cases where we have single-phase motors connected across two of the wires of the three-phase circuit, and sometimes we have lights connected so that in practise we should apply this method with caution.

Another point which the author does not bring out, but which is important, is that, after a meter has been in service for some time, we do not know whether it is in correct calibration or not. The author assumes all through his paper that the meter he is dealing with is correct. We can very readily imagine the case of an incorrect meter, for example, one which is badly out on lag, which would not answer correctly the test given here by the author. Therefore, in practise we must bear in mind, the balanced condition of the load and whether the meter is correctly or incorrectly calibrated.

L. W. Chubb: We must remember that there are two classes of men that take care of meter connections—there is the engineer who knows the vector relation of the voltage and current, and if he gets irregular results in one way, he can usually ferret out what is the matter, either by symmetry of connections or by common horse sense. The station man who gets into trouble, must be provided with some rule of thumb method which will give him results and not require basic knowledge of the principles involved. For this reason I think Mr. Kouwenhoven's scheme of reversing the potential coils for two classes of meters, or else opening the current between the meter and power in the other class, is of great value.

The requirements for balanced load in the majority of the work is, as Mr. Pratt says, a handicap. A balanced load on such a thing as an induction motor, or light running synchronous machine, is rare. If the field distribution in the motor does not agree with the line wave, there will be quite a big distortion and an unbalancing of currents with a very small change in phase and voltage. I do not believe this is a serious handicap, however, as you can estimate about what load you have, and if the meter comes nearly to a standstill, you know that the connection is probably right. The same is true for a meter a little bit out of calibration in the two parts, as the last speaker has mentioned.

I think, that for the engineer who goes out on a meter job and wants to find out what is wrong, the old method of opening one element of the polyphase meter and then the other is pretty good. You can usually get a load, balanced or unbalanced, which will have a power factor both above and below 0.5. For instance, the usual transformer of today on open circuit is run at such an induction that the exciting current is below 0.5 power factor. It is easy enough to put additional load on the transformer, and take another reading at a power factor above 0.5 so that opening one element at a time, with the two tests, will give quite a reliable result.

Comfort A. Adams: The subject of polyphase meter connection is so often made unnecessarily complicated that I am going to take enough time to explain what seems to be the natural and simple point of view, which I have employed for more than twenty years.

Label the mains of a three-phase system, a, b and c. Count the currents in a and b as positive when flowing outwards from the source and the current in c positive backwards. Then will $i_a + i_b = i_c$ at every instant, and c may be looked upon as the common return for a and b. The total power flowing outwards from the source will then be that of two circuits ac and bc, or stated in symbols, $e_{ac}\, i_a + e_{bc}\, i_b$, which holds for every instant of time irrespective of whether the system carries direct, alternating or pulsating current.

The two single-phase wattmeters or the two parts of a three-phase wattmeter connected with their currents coils in *a* and *b* and their pressure coils across *ac* and *bc* respectively in the direction indicated by the symbols, will measure the average values of $e_{ac}\, i_a$ and $e_{bc}\, ib$ respectively, or a three-phase wattmeter will indicate the sum of these, *i. e.*, the total power flow of the system in the direction indicated. If the corresponding terminals ± of the current and pressure coils of each meter are so indicated or implied by their location, it is only necessary to connect the two current coils in the lines *a* and *b* in the direction of power flow and the corresponding pressure coils in the directions *ac* and *bc*. If the direction of power flow is not known, it may be assumed and connections made accordingly. If the assumption is correct, the meter will read or run positively, otherwise either both current coil connections or both pressure coil connections should be reversed.

The above proof of the two wattmeter method of three-phase power measurement as well as the resulting conclusions as to the method of connection, is absolutely rigid and general for any wave shape or no wave shape. Moreover, it is directly applicable to a system of n wires in which one is looked upon as the common return for $n - 1$ phases, and the power can be measured by $n - 1$ wattmeters (or wattmeter elements of a polyphase wattmeter) connected as above indicated for the three-phase case.

I realize that the problem faced by the meter man is not the same as that faced by the laboratory man; but I feel quite sure that even the practical meter man would find his problem vastly simplified if he could acquire the above described natural point of view.

The idea is not at all a new one, but so few engineers seem to make use of it, that I am impelled by my teacher's instinct to set it forth again.

W. B. Kouwenhoven: As stated in the paper, the term correct, refers only to the direction of rotation of the disc of the watt-hour meter used in this investigation, and has nothing whatever to do with the accuracy of the meter. The meter used was not calibrated before making the investigation and it had seen a number of years of service. I do not know whether the two single-phase elements had exactly the same characteristics or not. However, their characteristics were sufficiently alike to cause the meter to stop when the voltage connections to phases 1 and 2 were interchanged. If a polyphase watt-hour meter is so badly out of adjustment that it will not answer correctly to the test although connected properly: then its failure to meet the test will immediately indicate that there is something wrong with the meter itself.

As Mr. Chubb pointed out, a slight unbalancing of a three-phase load such as is often found in induction motors, especially when operating on light loads, is not serious, and the check produced by the interchange of the voltage leads will identify the correct connections. Part of the investigation was carried on with induction motors as load, and part with synchronous motors, and in neither case was there the slightest difficulty in recognizing the correct connections when the check was applied. I do not know the amount of unbalancing that would prove serious. The correctness of the connections on balanced or unbalanced three-phase circuits for any class of meter may be checked by removing the fuses from the line as described in the paper.

If a polyphase watt-hour meter is placed in a circuit where no instrument transformers are required, then its proper connection, as Professor Adams points out, is comparatively simple. If two voltage and two current transformers are added to the circuit then the connections become difficult and a check is necessary.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 9, 1916.

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THE TRUE NATURE OF SPEECH

With Application to a Voice-Operated Phonographic Alphabet Writing Machine

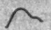
BY JOHN B. FLOWERS

ABSTRACT OF PAPER

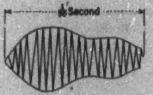
That speech is a rapid variation in intensity of the voice and mouth-tones according to definite sound patterns called letters of the alphabet, is proved, by showing that speech is the result of action of the mouth-parts in varying the intensity of the voice and mouth-tones, and through photographs taken with the string-galvanometer of each letter sound of the alphabet, showing definitely the characteristic variation in intensity of tone for each letter of the alphabet. From the curves, the phonographic alphabet is obtained by measuring the variations in intensity of the main tone of the record.

A design for a voice-operated phonographic alphabet writing machine is described. The object of this device is to record speech automatically in ink on paper in the form of an easily read compact system of natural characters called the phonographic alphabet. Its design comprises a high-power telephone transmitter controlling electric resonator circuits, the intensity of currents in which is measured by the vibration of mirrors reflecting light upon a selenium cell connected to a special recording pen.

DEFINITION OF SPEECH

SPEECH is a rapid variation in amplitude of one or more tones, there being a definite form of variation making a pattern for each letter sound of the alphabet. These patterns are not formed by the superposing of tones of different pitch to give a certain quality to the tone but by a definite form of variation in the amplitude of a single tone or tones. This previously unknown form of variation of amplitude, quite different from the ordinary change from soft to loud, should be called the speech-variation. What is meant is that if a tone of a pitch of say 1000 cycles per second commences in such a manner that the first 10 to 20 cycles vary in intensity after the definite pattern , the sound *b* will be produced and heard.

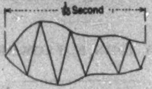
Thus:



20 CYCLES OF A 1000-CYCLE TONE

But no matter what the pitch of the tone, if its intensity is made to vary according to this definite pattern in a *small fraction of a second*, the sound *b* will be produced.

Thus:



5 CYCLES OF A 250-CYCLE TONE

When we speak the letter *b*, the fundamental tone and the overtones of the vocal chords together with the mouth-tones are all varied at the same instant of time according to the definite pattern . The same is true for each letter sound of the alphabet, as will appear in the table of patterns of the letters of the alphabet called the phonographic alphabet on another page:

In other words, if an open reed-organ pipe of, say, middle C pitch were blown and at its large open end were placed a mechanical device like the human mouth for opening, varying the opening, and closing the opening, and trilling and varying the air pressure, the organ pipe would speak like a human being, with wonderful power and majesty.

We quote Helmholtz: "Sensations of Tone," pages 66-67-68. "There has been a general inclination to credit quality with all possible peculiarities of musical tones that were not evidently due to force and pitch. But very slight consideration will suffice to show that many of these peculiarities of musical tones depend upon the way in which they begin and end. The methods of attacking and releasing tones are sometimes so characteristic, that for the human voice they have been noted by a series of different letters. To these belong the explosive consonants *B*, *D*, *G*, and *P*, *T*, *K*. The effects of these letters are produced by opening the closed, or closing the open passage through the mouth. For *B* and *P* the closure is made by the lips, for *D* and *T* by the tongue and upper teeth, and *G* and *K* by the back of the tongue and soft palate. In wind instruments where the tones are maintained by a stream of air, we generally hear more or less whizzing and hissing of the air which breaks against the sharp edges of the mouthpiece. It is well known that most consonants in human speech are characterized by the maintenance of similar noises, as F, V; S, Z; Th in thin and in then; the Scotch and German guttural CH, and Dutch G. For some the tone is made still more irregular by trilling parts of the mouth, as for R and L. In the case of R the stream of air is periodically entirely interrupted by trilling the uvula, or the tip of the tongue; and we thus obtain an intermitting sound to which these interruptions give a peculiar jarring character. In the case of L the soft side edges of the tongue are moved by the stream of air, and, without completely interrupting the tone, produce inequalities in its strength. The formation of M and N in so far resembles that of vowels, that no noise of wind is generated in any part of the cavity of the mouth, which is perfectly closed, and the sound of the voice escapes through the nose."

Proof that a Definite Fixed Pitch is Not the Chief Characteristic of Individual Letter Sounds

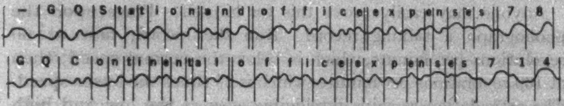
Anyone may easily prove this for himself. Place upon the phonograph a talking record. Run the record, first at 60 revolutions per minute, which is below the normal speed, then at 160 revolutions per minute, which is 2⅔ times the lower speed. The articulation remains intelligible even at the low and high speeds. The pitches of all speech sounds at the high speed of the record are nearly an octave and a half above the pitches at the low speed. Hence if but one fixed pitch was characteristic of each letter sound, the speech would have been absolutely unintelligible. But the speech was entirely intelligible and therefore pitch is not the distinguishing element between letter sounds.

Definition of Vowels and Consonants

A vowel is a definite sound pattern which repeats itself at intervals, while a consonant is a definite sound pattern occuring but once. The consonant sound pattern must exist at least for 0.01 second, in order to be perceived by the brain, 0.01 second being the minimum perception time for speech sounds. The vowel sound patterns proper, are about 0.01 second in duration, but as they repeat themselves again and again, may be of any duration the speaker desires. Under this definition, the consonants are b, c = k, d, g, j, k, p, t, and the vowels are, a, c = s, e, f, h, i, l, m, n, o, r, s, u, v, w = $\overline{\text{uo}}$, y, z.

Written language is made up of consecutive pattern pictures, one pattern or form standing for each letter of the alphabet, and the eye is able to distinguish between them if they approximate the standard form. Likewise, spoken language is made up of consecutive pattern pictures, one pattern or form standing for each letter of the alphabet, and I show in another paper not yet published, how the ear is able to distinguish between them when they approximate a standard form.

In reading a submarine cable message on the tape, the eye must pick out the pattern forms of each letter. That the eye can read these messages as fast as ordinary writing is known to all cable operators. Spoken language is similarly a succession of these different pattern forms, strung along one after the other, and the ear distinguishes each of these pattern forms as it arrives in the consecutive order of utterance, even as the eye distinguishes pattern forms of written or submarine cable language.


– G Q S t a t i o n a n d o f f i c e e x p e n s e s 7 8
G Q C o n t i n e n t a l o f f i c e e x p e n s e s 7 1 4

Cable Message Received by the W. U. Telegraph Co., February 11, 1915, Over an Atlantic Cable

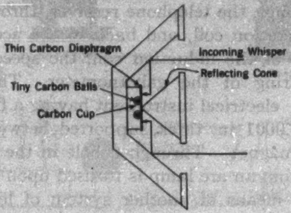
Speech may be whispered using no voice (without movement of the vocal chords). This fact was determined by actual observation of quiet vocal chords during a whispered word, "ah."

Distinction between Speech and Voice

Note the distinction between speech and voice and where each is produced, viz., voice by the vocal chords and speech through variation in the intensity of the compressed air forced through the throat, mouth, and nasal cavity. This variation in intensity is accomplished by the action of the muscles of the throat and mouth. Each person has a slightly different pitch of voice, men low and women high. An average man's voice has a pitch lying between 85 and 160 complete vibrations per second, while the average woman's voice has a pitch lying between 150 and 320 complete vibrations per second. Thus, the pitch of one person's voice is different from another's.

But speech may be produced by whispering, that is, using no voice, and whispered speech always has the same sound, no matter who is the speaker, man or woman. Any person can determine this by his own observation, getting someone to whisper with him and comparing the sound of the whispers. No difference in the sound of the whispers can be heard. In other words, during a whisper, speech is independent of the vocal chord action.

All previous speech records have been taken of spoken or sung words and none of whispered words on account of the lack of instruments sufficiently sensitive to record whispered speech. The resulting spoken records contained the fundamental tones and overtones of the vocal chords as well as the mouth-tones and their variations combined in so complex a curve that no one has as yet succeeded in deciphering them.



Section of Acousticon Transmitter for Whispered Speech

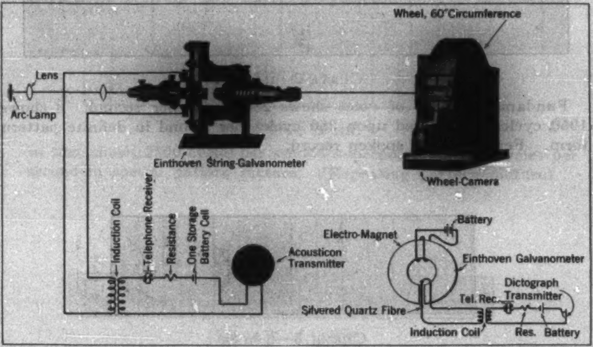
I found that the acousticon transmitter hooked up to the Einthoven string-galvanometer, as shown in the sketch herewith, were very satisfactory instruments for making records of whispered speech, as they are both marvelously sensitive instruments. On account of whispered speech being independent of vocal chord action, it was decided to make photographic records of it from which to determine by careful study the true nature of speech. It is evident that the whispered speech records will not show the voice-tones and overtones but will simply show the mouth-tones and their variations in intensity. It is easy to follow the variation in intensity of one or two tones on the whispered speech records and thus pick out the intensity pattern for each letter sound which I call the phonographic alphabet.

The diaphragm is made of very thin carbon and so covers the recesses in the carbon block, without touching it, as to prevent the tiny carbon balls from falling out. The sketch shows how the acousticon transmitter collects sound from a large area and by a reflecting system concentrates it on the middle of the carbon diaphragm. There is no spring pressing on the diaphragm and it is believed that the diaphragm moves like a piston with the rarefactions and compressions of the sound waves. It is a highly damped instrument due to the weight of the carbon balls pressing against the diaphragm resisting its motion.

DESCRIPTION OF METHOD OF MAKING WHISPERED SPEECH-PATTERN PICTURES

The acousticon transmitter was placed in a large sound-proof telephone booth and supported by suspension, free of all vibration. The diagram shows how the speech current flows from the acousticon through the storage battery cell, through the resistance, through the telephone receiver, through the primary side of the induction coil, and back to the acousticon; on the secondary side of the induction coil, the speech current flows through the string of the galvanometer. The string galvanometer is an electrical instrument having a fine silver-plated quartz fiber, 0.0001 in. thick, supported between two poles of a huge electromagnet. Through a hole in the magnet poles, a powerful ray from an arc lamp is focused upon this quartz fiber or string. By means of another system of lenses, the image of the string is focused upon a slot in the rotating drum-camera. When a speech-current flows through this galvanometer string, the string vibrates back and forth in a direction at right angles to the lines of force of the magnet, and its lightest motion is magnified 900 times by the lens system. The shadow of the string vibrates back and forth on the camera-shutter almost exactly in proportion to the speech sounds. The camera photographs the vibrating shadow of the galvanometer string. A word is whispered repeatedly, and the speech is listened to in the telephone receiver as a check on the articulation of the words. When the shadow of the galvanometer string moves back and forth about two inches, a lever is pressed, the electrically operated camera-shutter is held open for one revolution of the wheel and a photographic record, five feet long, of the word whispered is obtained. Extra-rapid film was exposed and good photographs obtained at rates varying from 1000 feet to one mile per minute. The rate of 1080 ft. was used mostly in this work as it gave a record with good intervals between crests of speech-waves, the best record to analyze. By interrupting the light from the arc lamp, 500 times per second, vertical lines were photographed upon the film at intervals of 0.002 second by a specially constructed time-wheel, for the necessary time record.

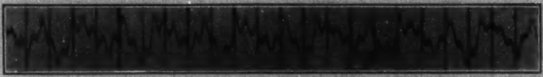
For a consideration of the theory of the string galvanometer, I refer to Dr. A. C. Crehore on the "Theory of the String Galvanometer," *Phil. Mag.*, vol. 28, August, 1914. The amount of air and electromagnetic damping of the movement of the galvanometer string was large enough, so that the motion of the string corresponded almost exactly to every component of the impressed speech currents, and the resulting speech records should be regarded as being as nearly correct records of speech as can be obtained by any recording instrument.


Wheel, 60"Circumference
Lens
Arc-Lamp
Einthoven String-Galvanometer
Wheel-Camera
Induction Coil
Telephone Receiver
Resistance
One Storage Battery Cell
Acousticon Transmitter
Battery
Electro-Magnet
Einthoven Galvanometer
Dictograph Transmitter
Tel. Rec.
Silvered Quartz Fibre
Induction Coil
Res.
Battery

Speech patterns of the same letter sound are almost exactly identical for all persons and independent of age or sex of speaker. Five hundred records were obtained of three men's speech and one woman's speech which prove this.

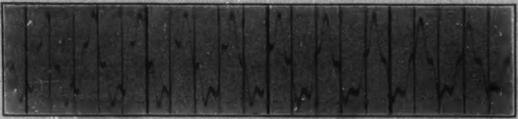
THE PATTERN FORMS OF THE NATURAL ALPHABET

Each of the letters has its own pattern form. All following records are of whispered speech, except Nos. 1 and 2.



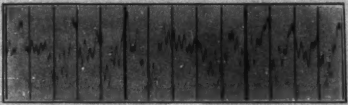
Curve 1—ū in yū

Showing fundamental tone of voice to be 140 to 200 cycles per second. ū equals 1100 cycles per second superposed upon the lower note in definite pattern form. Male voice, spoken record.



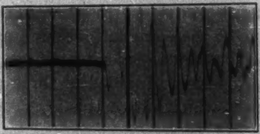
Curve 2—ū in yū

Fundamental tone of voice shows 250 cycles per second. ū shows 1050 cycles superposed upon 250 cycles per second in definite pattern form. Female voice, spoken record.



Curve 3—ā in āō

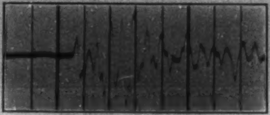
ā shows 2500 cycles per second superposed upon 500 cycles per second in definite pattern form. (Repeating pattern picture.)



Curve 4—b in bāy

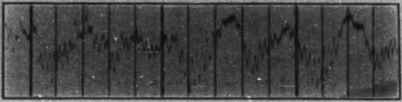
b shows special pattern picture.

c equals s.



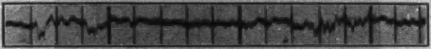
CURVE 5—d in dāy

d shows special pattern picture.



CURVE 6—ē in mē

e in me, shows 2500 cycles per second superposed on 200 cycles per second in special pattern picture. (Repeating pattern picture).

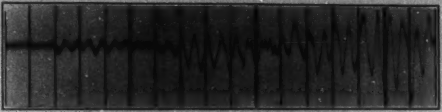


CURVE 7—f in fēe

f in fēe, shows alternation of 1000 and 2500 cycles, special pattern. (Repeating).

CURVE 8—g in gō

g in go, shows special pattern picture.



Curve 9—h in hĭ

h in hi, shows special pattern picture. (Repeating).

Curve 10—ī in mī

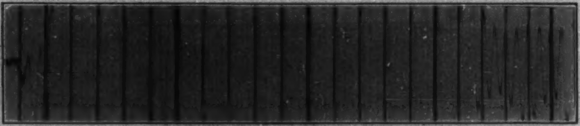
ī shows 1700 cycles in special pattern picture. (Repeating).

Curve 11—ĭ in hĭ

i shows 2600 to 2700 cycles in special pattern picture. (Repeating).

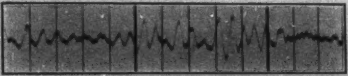
Curve 12—j in Jōe

i shows 3000 cycles for 0.01 sec., 2500 cycles for 0.05 second, 2000 cycles for 0.01 second in special pattern picture.



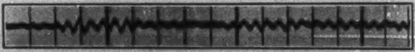
Curve 13—k in kō

k shows special pattern picture.



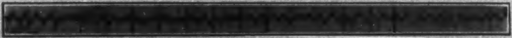
Curve 14—l in lō

l shows alternation of 2500 and 1000 cycles per second in special pattern picture. (Repeating).



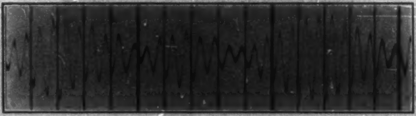
Curve 15—m in mȳ

m shows 1200 cycles for 0.01 second, silence 0.006 second, 1200 cycles for 0.01 second in special pattern picture. (Repeating).



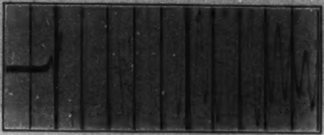
Curve 16—n in nē

n shows 1100 cycles with silence following in special pattern picture. (Repeating).



Curve 17—ō in tōe

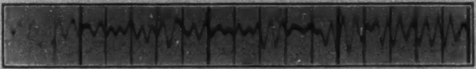
ō shows 1000 cycles in special pattern picture. (Repeating).



Curve 18—p in pō

p shows special pattern picture.

q equals ky̆ū.

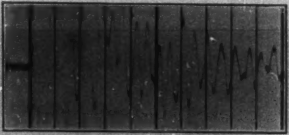


Curve 19—r in rō

r shows alternation of 1000 and 1250 cycles in special pattern picture. (Repeating).

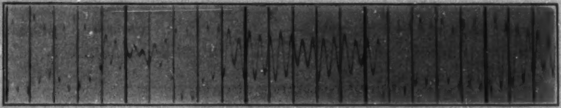
Curve 20—s in say

s shows 1000 alternating with 2000 cycles per second superposed upon 1000 cycles per second. (Repeating).



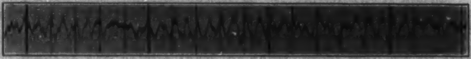
Curve 21—t in tō

t shows special pattern picture.



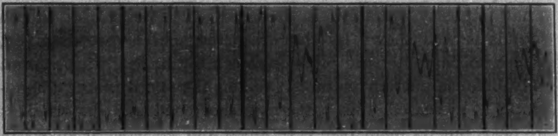
Curve 22—ū in tū

ū shows 1100 cycles in special pattern picture. (Repeating).



Curve 23—v in vē

v shows 1000 and 2500 cycles alternating in special pattern picture. (Repeating).



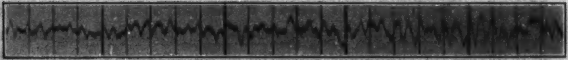
Curve 24—ūō = w in wē

w in we, shows ū equals 1050 cycles; same special pattern as ū passing into ō equals 1000 cycles. (Repeating).

x equals ĕks

ȳ equals ū ī

y̆ equals ĭ



Curve 25—z in zee

z shows 5000 and 2000 cycles per second alternating over 1000 cycles per second in special pattern picture. (Repeating).

From Helmholtz's formula for resonance of a spherical cavity with a small opening,

$$n = a\sqrt{\frac{3r}{8\pi^3 R^3}},$$

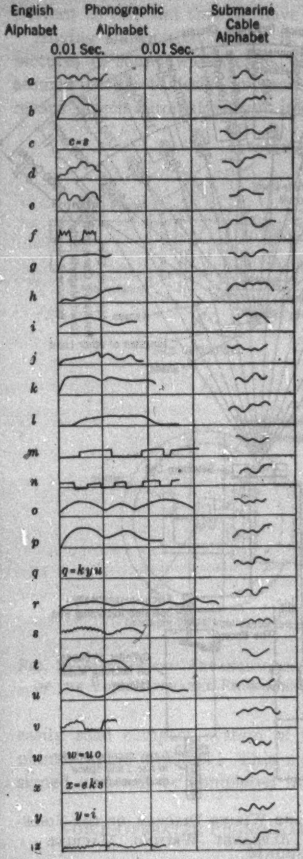
where n equals pitch of resonance of cavity,
r equals radius of opening of cavity,
R equals radius of cavity,
a equals 33,226 centimeters,

we can calculate the natural resonance tones of the mouth while uttering speech. I have done this and find that the resonance tones for the mouth vary from 800 to 3000 cycles per second, depending on the opening of the mouth. From our records, we find the pitches upon which whispered speech is uttered to be also from 1000 to 3000 cycles per second. This only shows, however, that pitch is an unavoidable characteristic of speech sounds. From the known facts, that a phonograph talking record may be run at more than twice the normal speed so that the speech tones must vary through more than a full octave and the speech is still quite intelligible, it is conclusive that pitch is not the main characteristic of speech sounds. That intensity variation is the main characteristic of speech sounds is well shown by the whispered speech records given, where no characteristic pitch is shown for b, d, g, k, p, t, but only definite pattern pictures. When the speed of the phonograph is increased, this pattern is shortened and distorted as we hear, but its main form is retained and we judge it as nearly the same as the sound at the correct speed and therefore are able to understand the speech. The pitch of speech sounds, then, only exists as a carrier of the speech-variations. In another paper not yet published on the Nature of Hearing and Perception, it is shown how pattern forms operate memory cells, and how we thus perceive the letter sounds of speech.

In general, the pattern form persists for at least 0.01 second and if the letter sound is sustained, the pattern repeats itself again and again. See pattern picture of letter ō sound, curve No. 17. One-hundredth second is the perception time. This is proved in the paper mentioned above. Therefore the mouth is a device for producing patterns of the necessary length and repeating them for sure perception.

Repetitions of pattern pictures of letter sounds (several times to make up a letter sound; see record of vowel ō, curve

No. 17,) are due to simultaneous excitatory and inhibitory action of impulses on same or opposing muscles in the mouth or throat. At one moment excitatory impulse overbalances inhibitory impulse, then a maximum appears on the speech curve; when the excitatory and inhibitory impulses balance by interference (equal pull on muscle) no or little amplitude is shown on ō curve. "A slight and rapid muscle tremor is regularly produced by the simultaneous play of excitation and inhibition on one muscle, just as 'progression' and other rhythmic movements are regularly produced by the simultaneous play of excitation and inhibition on antagonistic muscle pairs. One muscle can actually receive excitatory and inhibitory influences simultaneously, and this condition results in a peculiar and characteristic muscle 'tremor'." (Sherrington C. S., "Nervous Rhythm," Proc. Roy. Soc., 1913, Ser. B, 86, 219-232; Forbes, A., "Reflex Rhythm induced by concurrent excitation and inhibition," Proc. Roy. Soc, 1912, Ser. B, 85, 289-298.)



The repeated use of patterns is the physiological basis of memory.

I conclude from an exhaustive search of 500 vowel and consonant curves, that an accumulator or memory cell exists in the brain for each letter sound, detecting a definite picture

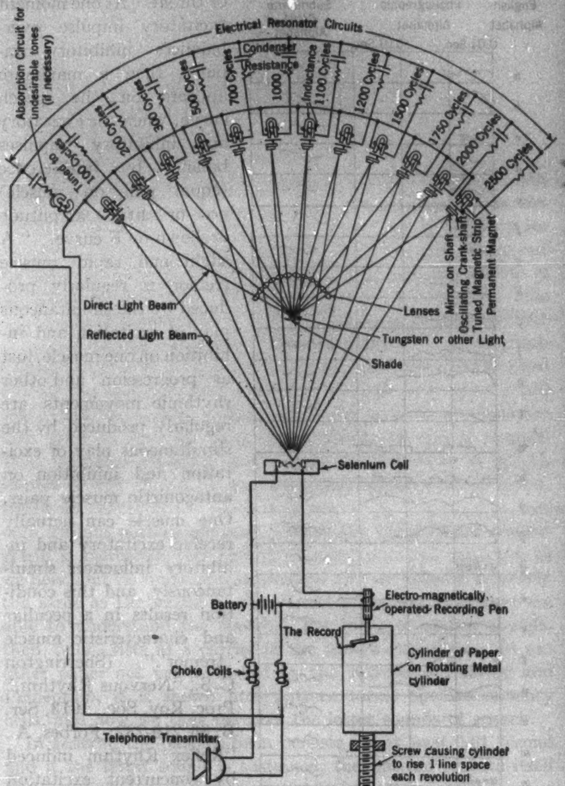
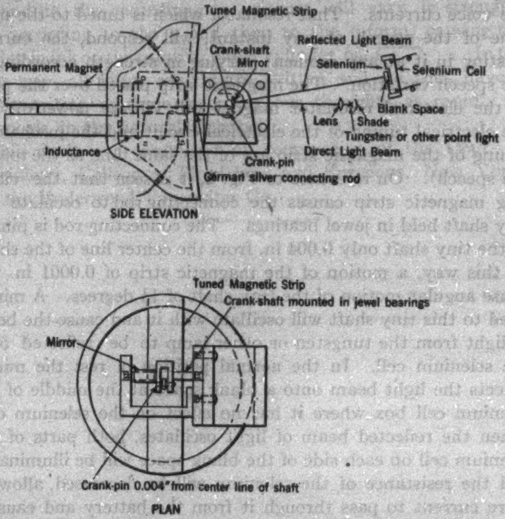

Electrical Resonator Circuits
Absorption Circuit for undesirable tones (if necessary)
Tuned to 100 Cycles
200 Cycles
300 Cycles
500 Cycles
700 Cycles
1000
Condenser
Resistance
Inductance
1100 Cycles
1200 Cycles
1500 Cycles
1750 Cycles
2000 Cycles
2500 Cycles
Mirror on Shaft
Oscillating Crank-shaft
Tuned Magnetic Strip
Permanent Magnet
Direct Light Beam
Reflected Light Beam
Lenses
Tungsten or other Light
Shade
Selenium Cell
Battery
Electro-magnetically operated Recording Pen
The Record
Cylinder of Paper on Rotating Metal cylinder
Choke Coils
Telephone Transmitter
Screw causing cylinder to rise 1 line space each revolution

FIG. 1—GENERAL ARRANGEMENT AND WIRING DIAGRAM OF THE VOICE-OPERATED PHONOGRAPHIC ALPHABET WRITING MACHINE

pattern, such as that of the letter $\overline{o}$ which has a simple character of varying amplitudes, but repeats this character or picture pattern about 100 times a second. Since it takes 0.01 second to perceive a picture pattern (perception time for sounds), this seems the right length of time (0.01 second) for a definite picture pattern to last and then to have repetition.

Having shown that speech is made up of a set of pattern pictures of sound waves called the phonographic alphabet, it seemed feasible to design and construct a machine which would record speech automatically in ink on paper in the form of this easily read compact system of natural characters called the phonographic alphabet. This machine has been carefully designed and will be completed in the near future.


Tuned Magnetic Strip
Reflected Light Beam
Crank-shaft
Mirror
Selenium
Selenium Cell
Permanent Magnet
Blank Space
Lens
Shade
Tungsten or other point light
Inductance
Direct Light Beam
Crank-pin
German silver connecting rod
Tuned Magnetic Strip
Crank-shaft mounted in jewel bearings
Mirror
Crank-pin 0.004" from center line of shaft

SIDE ELEVATION

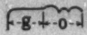
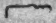
PLAN

FIG. 2—MECHANICAL ARRANGEMENT OF MIRROR-MOVING MECHANISM OF THE VOICE-OPERATED PHONOGRAPHIC ALPHABET WRITING MACHINE

VOICE-OPERATED PHONOGRAPHIC ALPHABET WRITING MACHINE

Fig. 1 shows a wiring diagram and general arrangement of the elements of this machine. Notation on the sketch explains the function of the different parts of the device. Fig. 2, in plan and elevation, shows the mechanical arrangement of each electrical resonator circuit and how the resistance of the selenium cell is varied by the differences in the amount of light coming from the vibrating mirrors.

Method of Operation. On reference to Fig. 1, it is evident that by talking into the telephone transmitter, speech currents are caused to flow into the electrical resonator circuits. An audion may be used as a relay if desired, to increase the strength of the voice currents. That resonator which is tuned to the main tone of the speech at any instant, will respond, the current existing in it at any moment varying in strength according to the speech-variation. The magnetic strip placed over the poles of the electrical resonator magnet will vibrate powerfully (if the electrical tuning of the electrical circuit and the mechanical tuning of the magnetic strip are of the same tone as the tone of the speech). On reference to Fig. 2, it is seen that the vibrating magnetic strip causes the connecting rod to oscillate the tiny shaft held in jewel bearings. The connecting rod is pinned to the tiny shaft only 0.004 in. from the center line of the shaft. In this way, a motion of the magnetic strip of 0.0001 in. will cause angular motion of the tiny shaft of 1½ degrees. A mirror fixed to this tiny shaft will oscillate with it and cause the beam of light from the tungsten or other lamp to be reflected onto the selenium cell. In the normal position of rest the mirror reflects the light beam onto a blank space at the middle of the selenium cell box where it has no effect on the selenium cell. When the reflected beam of light oscillates, both parts of the selenium cell on each side of the blank space will be illuminated and the resistance of the selenium will be decreased, allowing more current to pass through it from the battery and causing the electromagnetic recording pen to trace a wavy line on the paper sheet fastened to the revolving platen.

To illustrate the method of operation: Let the word "go" be spoken into the telephone transmitter. From our table of the letters of the phonographic alphabet we shall expect the recording pen to write "go" in the form of  . It is known from my research that there are present in the sound of a man's speech, principal tones of 100 cycles per second (the fundamental tone of a man's voice), 200 cycles per second (the 1st overtone of the man's voice), and a tone of approximately 1000 cycles per second (the resonance tone of the mouth for the o-position.) These three tones will be moulded or varied in intensity simultaneously by the muscles of the throat and mouth, first in the g-form (a sudden explosion of the three tones) and then in the o-form (a quick waxing and waning of the three tones.) Three tuned electrical resonating circuits marked respectively 100, 200 and 1000 cycles will simultaneously respond to the three tones and three beams of light will oscillate over the face of the selenium cell, each vibrating after the same pattern at the same instant of time. The current in the selenium cell and in the recording-pen magnet will vary in strength, first according to the g and then to the o-form, causing the writing in ink on the rotating paper cylinder of  . In the same way, all letter sounds are written and we thus have a visible-writing machine recording our thoughts as rapidly as we speak, in the natural alphabet.

This work was conducted by cooperation of the Dept. of Physiology, College of Physicians and Surgeons, New York, and the Underwood Typewriter Co.

DISCUSSION ON "THE TRUE NATURE OF SPEECH" (FLOWERS), NEW YORK, FEB. 9, 1916

H. B. Williams: Mr. Flowers has made a definite and valuable contribution to the physiology of speech by showing that in whispered speech the vowel frequencies are very nearly the same for all adult individuals.

His theory that the peculiar curves he obtains at the beginning of spoken or whispered syllables where the first sound in a consonant is due to variations in intensity of the vowel sounds, is ingenious and interesting, but I believe the curves admit of a different interpretation. Such curves could undoubtedly be analyzed into a number of higher frequencies and the fact that in all of the curves of consonant sounds there are marked departures from the sine wave form lends color to the view that higher frequencies may be present.

To record all frequencies of a complicated sound in proper relative amplitude, the recording instrument should have a natural period higher than the highest component by at least one power of ten.

The galvanometer employed by Mr. Flowers for most of his work had a natural period not far from 250 and was critically damped. If the accessory apparatus was arranged so as to give satisfactory amplitude when this instrument was executing forced vibrations at the rate say of 2000, a rate of four or five times that would be almost entirely smoothed out. For this reason I think it unwise to draw too sweeping conclusions from records obtained by this method.

The experiment of running a phonograph at different speeds and securing clear articulation might be also explained by the assumption that the sound is recognized by the association of a number of frequencies which bear a definite relation to each other. No one, so far as I am aware, has ever assumed that the speech sounds were characterized by a definite absolute frequency.

L. T. Robinson: It seems to me in the paper now before us and in a great many previous writings, we have gone too far on the assumption that the electrical wave was the sound wave. There is enough difficulty, perhaps, in recording the electrical wave; but there is a tremendous difficulty, in my own mind, in making that leap from the sound wave to the electrical wave. I have done enough work in this line to convince myself that in most cases the sound wave and the electrical wave are quite different.

Albert C. Crehore: I have had some experience with the galvanometer which has made these records, for another kind of work, a study of the nerve transmission. Here the galvanometer is practically short circuited through the induction coil and for that reason the electromagnetic damping is very great.

In the case of the work I was doing, there are ten thousand, twenty thousand or thirty thousand ohms in a little section of the nerve that comes in so that it is a comparatively undamped vibration.

There is one thing which Mr. Flower's work has almost established, and that is where he has differentiated between whispered speech and speech involving the vocal chords. The consistency obtained in these curves for whispered speech in different individuals, whether male or female, is very striking, and there must be some foundation for it. I do not mean to have you understand that the curves which are here given represent accurately the current or the sound wave necessarily. Whether they do or not, you can compare the consistency of them—I mean to say if under similar conditions, you have a constant result, it has a meaning irrespective of the fact whether it is a true record or not. In using such a galvanometer we always take the control, that is, place a known potential suddenly across the terminals and observe the deflection and time record. This is invariably done during the course of any work with the galvanometer, because you can change the tension of the string at a moment's notice. I would like to see a control curve showing the condition of the galvanometer for these records. I assume that the string was slack and had a very low period of vibration, necessarily, because there is not sufficient energy to get results otherwise. But under these conditions we are recording forces or vibrations with a string which is absolutely damped, and there would be no over-shooting of the string if you should deflect it. Imagine the string at the top point of any one of the curves, where the force suddenly reverses; if the same force had been left on indefinitely, the curve would have risen up far beyond its base, so that it is not a true record of the force that is there at any given moment if we calibrate the instrument with direct currents. The average force is practically zero, and so you have a wandering zero. I do not think that detracts to any material extent from the deductions you can make from the records, even though the curve which Mr. Flowers gives as an alphabet may have to be modified.

William Maver, Jr.: In Dr. William Hanna Thompson's work "Brain and Personality," in debating the manner in which the nerves and muscles of the body are trained and controlled, he remarks that certain instances to which he has referred of highly trained muscles cannot be compared for complexity and difficulty with the training of the muscular organ, the tongue, for the movements necessary for articulate speech. An animated orator, he adds, has to make a greater number of rapidly succeeding and yet perfectly adjusted contractions and relaxations of his muscles of articulation than any famous performer on a musical instrument. Mr. Flowers apparently has accomplished the difficult feat of photographing the rapidly varying vibrations due to these rapid yet perfectly adjusted contractions and relaxations of the muscles of articulation.

In accord with other writers on the general subject of the fixation of knowledge in the brain, Mr. Flowers expresses his belief that a particular brain cell receives the impression of a given pattern picture. In this relation, Mr. Flowers later points out that when one becomes familiar with the phonographic alphabet he will be able to read it as easily and as intelligently as the telegraph operator reads the signals used in submarine telegraphy.

We might find an analogy to the view that particular brain cells respond to given pattern pictures in the case of certain printing telegraph systems. For instance, the Baudot system, much used in Europe. In this system combinations of five pulsations of positive and negative current are transmitted over the wire for the letter of the alphabet, a different combination for each letter. According to the manner in which these pulsations of current arrive, certain relays will be operated, and these relays in turn will select the letter represented by a given combination of pulsations, by bringing the desired letter on a typewheel opposite a paper strip, on which the letter is immediately printed. This is termed in the art, selective printing telegraphy.

As a matter of interest, it is quite as accurate to say that the Morse telegraph is also a selective system of telegraphy, whether the signals transmitted by that system are received on a paper strip as dots or dashes, or by audible dots and dashes, so-called. In receiving messages by sound, the ear transmits the combinations of dots and dashes representing given letters of the alphabet to the brain cells that have been trained for this purpose, so-called memory cells, and the brain cells concerned respond to the given combination of signals, and we or the something within us which I think Dr. Thompson would term our personality, recognizes the signal for what it is meant. Correspondingly, the trained brain cells, or as we would say in telegraph phraseology, the properly adjusted brain cells, which receive through the eye their impressions of Mr. Flowers' phonographic alphabet, respond by vibrating or otherwise in such manner that again our personality recognizes the impressions for what they are meant.

Perhaps for the purpose of assisting in illustrating the foregoing, we can utilize Fig. 1 in Mr. Flower's paper. Let us consider the tuned electromagnets in the diagram as the equivalent of the memory cells of the brain which have been attuned or adjusted to special rates of vibration, or otherwise suitably adjusted, by frequent visual repetition of the pattern pictures. Now, whether the memory cells when stimulated by the pattern picture are the equivalent of a selenium cell or the equivalent of an electrically operated recording pen for the interpretation, deponent saith not. Perhaps Mr. Flowers will have some enlightenment for us on this subject in his forthcoming paper on the nature of hearing and perception.

William J. Hammer: Regarding Mr. Flowers application of the selenium cell in his work, permit me to say that while people with limited experience ridicule the employment of the selenium cell because of its unreliability, its inertia, etc., I wish to say that I have frequently demonstrated its reliability, and some of its many practical applications, were shown before the Institute at its joint meeting with the American Electrochemical Society on April 17th, 1903 during my lecture on "Radium, Selenium, etc.", at which time I operated 5-h.p. motors and generators, fired cannon, turned lights on and off, talked over a beam of light, etc., by means of selenium cells and an acetylene lamp, and the proper relays and switches.

As illustrating in a remarkable manner the sensitiveness of the selenium cell to sound recording reproductions and transmission, I beg to call the members' attention to Mr. Ernest Ruhmers photographophone which I described at my lecture in 1903, and which I personally operated in Berlin in 1902.

In these extraordinary experiments, when one talked in a telephone transmitter connected in a shunt circuit of an arc lamp it caused the light to vary as a manometric flame. The light beams were passed through a cylindrical lens in the front of a moving picture camera and photographed in striations of varying width and intensity upon the moving film. After the film was developed and put back into the box and the arc lamps replaced (but now burning steadily) the striations on the film acted like slats in a shutter to allow more or less light to pass through the film and to then fall upon a selenium cell in the back of the box. To this cell a pair of telephone receivers was connected, through the intermediary of which the original message could be distinctly heard.

Let me further remind the members of the comparatively recent and entirely successful transmission of pictures through the intermediary of the selenium cell, from Paris to London, across the English Channel, the pictures appearing in the London papers within a few hours.

L. W. Chubb: I have made some tests to check some of the present theories of speech and vowel sounds. The theory of constant frequency and mouth resonance for vowel sounds, was disproved both by the phonograph test, also tried by Mr. Flowers and by the singing of vowels at a note of higher fundamental frequency than the supposed frequency of the vowel. As an example the vowel "oo" is supposed to be represented by the resonance or amplification of harmonic frequencies around 400 cycles per second, and yet the vowel or a word containing it could be distinguished when sung several notes above high C.

The results of such tests and the disagreement between spoken and whispered vowel sound waves, makes me feel that the resonance at constant frequency, although present, is not the distinguishing feature of the sound.

Is it not possible that Mr. Flowers' pattern theory is correct and that the resonance of certain frequencies in certain sounds, is unconsciously produced by the speaker so as to combine adjacent harmonic components in such a way as to get a low frequency pattern or beat?

Comfort A. Adams: Dr. Kennelly has done a large amount of work, both theoretically and experimentally, in analyzing the connection between the vibration of a telephone receiver diaphram and the current producing it, as well as the relation of the deflection of an oscillograph system to the current producing it, over a wide range of frequencies. On the oscillograph end of this work, in which I have been much interested, we have found that the record is fairly accurate up to within a comparatively small percentage of resonance. That is, there must be no appreciable harmonics of that order in the current being measured. Theoretically the problem is extremely difficult when all the numerous variables are considered, but fairly reliable results can be obtained, when the limitations of the instrument are appreciated. Otherwise it is very easy to be badly misled by oscillograph records.

A. C. Crehore: In my remarks upon Mr. Flowers' paper, I had in mind chiefly the application of the string galvanometer for recording such waves as are shown in the illustrations in the paper. It seemed inopportune to introduce a theoretical discussion of the galvanometer in connection with this paper merely because I have worked out the theory of it. There is a great deal to be said about it and of a very complex nature. We have to study nothing less than the complex motions of a stretched string. Think of it, if you please, as a violin string set in motion not by the bow acting at a single point of the string, but by the magnetic field distributed in some way along most of the length of the string, the force thus being applied to many parts of the string simultaneously and in varying amounts, and we have a partial statement of the problem to be solved.

So, in my remarks, I had hoped that you would accept the statement as given without proofs that the movement of the string under the conditions imposed by Mr. Flowers' problem could not possibly be an exact reproduction either of the waves of sound or of the current in the string, but it might approximate it closely if the conditions were properly met. To have emphasized this point at some length by these proofs would have seemed to detract from the merits of Mr. Flowers' findings, for I believe it to be feasible to obtain results of some value with an instrument which does not record the exact sound waves but yet shows much valuable detail, as this instrument does. We may be assured that if similar results are obtained on the films in different instances the probability is very strong that similar sound-waves caused the records to be alike. This is where I think Mr. Flowers has made a real contribution to our knowledge.

It is my conviction that the records are at best approximations with all existing instruments and this is the reason that a theory of the instruments, is so much to be desired. It tells why the records are approximations and what must be done to make the approximation closer.

The way in which the magnetic field is distributed along the length of the string is of prime importance in the resulting motions of the string. In instruments as now constructed this field is uniform as nearly as this condition can be readily obtained over nearly the entire length of the string. If the field were exactly uniform the proof is very simple that the curve assumed by the string is the arc of a circle under the action of a steady direct current, no matter how great the deflection. This fact gives rise to certain complex motions of the string, each corresponding to the terms of a Fourier series expressing this circular arc, that is, when variable currents are applied. The simplest possible manner of the field distribution along the string, so far as the resulting motion of the string is concerned, is that of a sine-curve, the field strength being a maximum at the center and tapering according to the sine law towards both ends. With such a field the curve assumed by the string under the action of a direct current is also that of a curve of sines, which, therefore, is expressible by the first term only of a Fourier series. The motions of the string under these conditions are the simplest possible, and the complete solution of the motion of the string, for any kind of a current is known. This solution is complex enough, to be sure, but it is safe to use this solution as a basis for making certain deductions, and if it is apparent in this simpler case that the string can not follow exactly such sound waves as Mr. Flowers applies to it, so much the more would this be true for the more complex solution in the ordinary case of uniform field distribution. This solution in the case of the sine-wave distribution of the field for a simple harmonic e. m. f.

$$e = E_1 \cos \omega_1 t = f(t) \tag{1}$$

is, for the periodic portion of the motion alone,

$$y_1 = \frac{H_0 E}{\rho R} \frac{\cos(\omega_1 t - \epsilon_1)}{[(n_1^2 - \omega_1^2)^2 + k_1^2 \omega_1^2]^{\frac{1}{2}}} \sin \frac{\pi x}{l}, \tag{2}$$

where y is the deflection of any element of the string at the distance x from one end of it, and l the length of the string. H_0 is the strength of the magnetic field at its maximum point in the center of the string, ρ the mass of the string per unit of length, and R the total resistance of the circuit, in which the inductance is supposed to be negligible. These and the other quantities in this equation except t are constants, and the equation gives the motion of the string as a function of the time. The phase angle ϵ_1 is such that

$$\tan \epsilon_1 = \frac{k_1 \omega_1}{n_1^2 - \omega_1^2}, \tag{3}$$

and the constants n_1 and k_1 in terms of the properties of the string and the air damping factor k are

$$n_1 = \frac{\pi}{l}\sqrt{\frac{T_1}{\rho}} \tag{4}$$

and

$$k_1 = k + \frac{H_0^2\, l}{2\,\rho\, R} \tag{5}$$

When the e. m. f. is a complex function of the time, it is expressible as a Fourier series of cosine terms, and the resulting complex motion of the string is then merely the sum of a series of terms, each similar to (**2**) in which ω_1 and ϵ_1 take different values, all other quantities remaining the same as before. An easy way to see these results is by means of specific examples, illustrated as curves. Since the observations on the string are usually made at its central point, where $x = l/2$, we may first simplify (**2**) above by making $\sin \frac{\pi x}{l} = 1$, and writing y_0 for y, this meaning the deflection of the center of the string. The curves that are instructive are the relations between the deflections of the string produced per unit of current as the frequency alone varies, keeping the resistance of the circuit constant. Curve I, Fig. 1, is such a curve plotted from (**2**), showing an increase in the deflection per ampere up to a critical frequency of $\frac{1000}{2\pi}$, and then rapidly falling off for a further increase. The character of this curve is much affected by the particular resistance originally assigned, and the resonance effect is more pronounced the greater the resistance. Curve II represents the same thing, the only difference being that the resistance originally chosen for the circuit is one-tenth of previous value and the impressed volts also one-tenth, the current being the same. Curve III

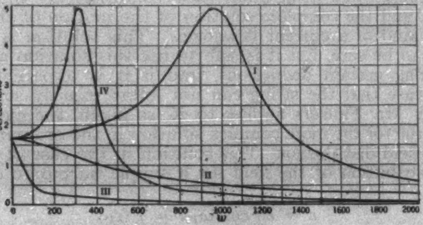


FIG. 1

shows a further decrease to a one-tenth value in the resistance and volts, the current being the same in the three curves. The resonance effect has entirely disappeared in these latter two curves. From (**2**) the maximum value of the deflection may be written

$$Y_1 = \frac{Y_0}{[(n_1^2 - \omega_1^2)^2 + k_1^2\,\omega_1^2]^{\frac{1}{2}}}\text{, where } Y_0 = \frac{H_0 E}{\rho R} \qquad (\mathbf{6})$$

or at the critical frequency, when $n_1 = \omega_1$, this is simplified to

$$Y_1 = \frac{Y_0}{k_1\,\omega_1} = \frac{H_0\,E}{\rho\,R\,\omega_1\left(k + \frac{H_0^2\,l}{2\,\rho\,R}\right)} \qquad (\mathbf{7})$$

And if the damping factor $\frac{H_0^2\,l}{2\,\rho\,R}$ is small compared with the quantity k, the air damping factor, the deflection at this critical frequency with the same current and frequency is almost exactly inversely as the resistance of the circuit, as is evident in these three curves.

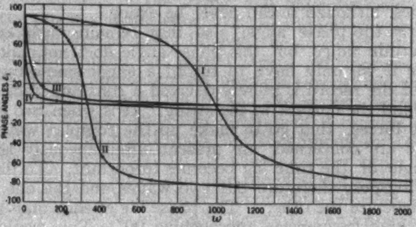


FIG. 2

If the value of n_1 is reduced to one third of its value for these three curves by increasing the tension on the string, we would get a curve like IV for the same resistance in circuit as that in Curve I. This shows a much sharper resonance point. The voltage and current for this curve are, however, increased so as to give the same deflection for a direct current or a zero frequency.

Another set of instructive curves are those showing the changes in the phase angle ϵ_1 (**3**) with a change in the frequency, other things remaining unchanged. Some of these are shown in Fig. **2**, Curve I being that corresponding to Curve I of Fig. 1, where the critical frequency is such that $\omega_1 = 1000$, and resistance the same as in that curve. A decrease in the resistance alone will change this curve into one like Curve II. Curves III and IV are a similar pair for the case of greater string tension, III corresponding to IV in Fig. 1. The phase angle is zero in each case at the critical frequency, and changes from 90° at zero frequency through zero, to approach $-90°$ at very great frequencies.

We now come to the consideration of the case that applies to the condition of the galvanometer in Mr. Flower's records. The frequencies that he records are far above the critical frequency, which is determined by the string tension, and we are then working at a point on the curves at some distance to the right of the peaks of the deflection curves in Fig. 1. If we had to deal with a single sine-wave voltage alone of varying intensity and definite frequency, the record would give deflections strictly proportional to this voltage, but if the frequency decreased we would get a slightly different deflection for the same voltage. The fact, however, that these curves may change very slowly in height with an increase of frequency when we are far removed from the critical frequency goes to show that the approximation to proportionality may be fairly close over a certain range of frequencies, although it can never be exact.

Similarly the phase angle also may remain fairly constant over a certain range, but this phase angle does not make much difference if we only have to record a single-sine-wave. The making of the record is merely delayed a constant fraction of a cycle behind the current in the string. It is when two or more harmonic forces, that go to make up the complex waves with which we are concerned, are present simultaneously that the phase angle or the time lag becomes important. To illustrate the case suppose there are but two waves and the one double the frequency of the other. The phase lag of each may be very large for high frequencies approaching 90°. This would mean that the absolute shift in time would be twice as much for the slower wave as for the faster, and that their relative shift amounts to one quarter cycle of the higher frequency wave. If the original waves coincided in phase, the zeros of the higher frequency coming at the zeros and the maxima of the slower wave, they never would so coincide in the record, but the zeros of the lower frequency would come at the maxima of the higher frequency. This condition would not give anything like a true record of the original, but it might answer some purposes if one were studying one particular frequency.

Curve II, Fig. 2 shows, however, that this phase lag may not only be fairly constant over a considerable range but that it may also be zero over this range as well. In this condition the relative phases are not displaced and the record should approach quite closely the current in the string in form with the understanding that all the lower frequency waves are magnified in amplitude a little more than the higher ones. So we see that it is possible with a string galvanometer to record a complex wave in an approximately correct form but only approximate. It is evident, also, from the preceding remarks that it will not do to calibrate this galvanometer by means of a direct current, and expect that for each deflection observed in the high frequency record the current is the same as that due to a direct current of the same intensity. Curve III, Fig. 1 shows this. The current is the same throughout this curve, and the small deflection at the high frequencies is in great contrast to the large one at the origin where the current is steady. If at any point of the record save where the current is zero one should suddenly maintain the current then existing, fixed, the deflection of the string would in general go way out of the field, becoming very large. If, however, you are so well acquainted with your instrument as to know its constants and exactly what you are doing, the calibration with direct currents together with the use of a theory will give the deflections to be expected at any frequency.

I have illustrated this subject by the use of an ideal string galvanometer, the like of which does not exist, and have shown that we may only hope to get a fairly close approximation in any case to the current in the string, and have not said anything about the phase shifting effects of the induction coil and telephone transmitter as being beyond the scope of my remarks. If we should employ an actual string galvanometer, whose magnetic field is approximately uniform throughout the string, the approximation would not be so close as that obtained with this one. In skilled hands this instrument is capable of giving results that can be relied upon, but it is important to know its constants, and to understand the theory of it in order to arrive at those conditions which will give the closest approximation to any desired result. When there is a complete knowledge of these things it is possible to apply the theory to certain records, and correct the records to give the probable true currents in the string.

The curves which I have used to illustrate my remarks are not those which apply directly to the condition of the galvanometer as Mr. Flowers has used it. In his case the electromagnetic damping is the larger of the two, and in these curves I have supposed that the air damping is the greater.

J. B. Taylor: This paper may be discussed from several different points of view:

First, the connection between the nature of speech and electrical engineering.

Second, the correctness of the photographic records offered, as representing the form of the associated sound wave.

Third, the correctness and originality of the theory favored by the author based on these photographic records or on his other data.

Fourth, assuming the theory to be correct, how closely may the author's "pattern pictures" for the alphabet from *A* to *Z* be taken to represent the true patterns?

Fifth, can a voice-operated machine be made along the lines described to write definite, readable characters when spoken into?

The nature of speech is quite as proper a subject for consideration by electrical engineers as any of the problems of telephony, since for perfect speech transmission, there must be exact correspondence between the sound waves produced by the complex actions of the speech mechanism, the mechanical motions of telephone apparatus and also of the transmitted current as modified by resistance, reactance, capacity, permeability and hysteresis of iron, etc. Theoretical and practical difficulties all along the line prevent perfect sound transmission. The telephone user, conversing easily day after day, often fails to realize the dependence which is placed on context and is at a loss to explain the difficulty of understanding proper names, figures and unfamiliar words. Note the changes which have been made in telephone call letters in the attempt to reduce mistakes, and the special telephone language which is springing up to further assist in this direction. Any attempt to improve telephone apparatus and transmission or transformation conditions must have as foundation, knowledge of the essence of speech and a knowledge of the relative importance of the different factors, so that where compromise must be made, the more necessary speech factors will be the least disturbed. These remarks apply as well to " loud-speaking " telephones for train announcing and similar uses, and perhaps with even more force, to the rapidly developing field of radio-telephony where many new devices and remarkable transformations are brought into play.

Regarding the photographic records, it should be borne in mind that these were made with the help of a string galvanometer. While this has high current sensibility, as compared with an oscillograph, its natural period is perhaps 300 or 400 per second against the figures 6000 to 10,000 for the oscillograph. This would call for some correction on all of the curves, and indicate markedly different appearance in those, such as numbers 3, 6, 7, 11, 12, 14, 20, 23 and 25, where the author assigns frequencies of 2000 to 3000 cycles and in the last case up to 5000 cycles per second. No mention is made of the natural frequency of the acousticon transmitter and diaphragm with its connected parts and closely associated air cavity. In my study of sounds and telephone currents with the oscillograph, I have found the form and adjustment of the transmitter, a highly variable factor in the resulting record. For example, in A.I.E.E. TRANSACTIONS, Vol. XXVIII, 1909, Part II, page 1169 oscillograms are shown, made with different transmitters. Though the records differ greatly in appearance, the inexpert telephone user would probably notice no difference in the receiver.

Bearing on this criticism, Mr. Flowers has replied that the correctness of his records was checked by constructing a selenium cell phonograph and that the reproduced sound was distinguished as being the same vowel or consonant originally uttered. Such a test I believe shows merely that much liberty can be taken with the shape of a sound wave, as is actually done with the regular telephone, and still have recognizable speech. I base this statement principally on some tests in which several tandem conversions were made from electric current to sound, back to current and again to sound, with oscillograph examination at the different stages.

Many experimenters and observers have studied the nature of speech and numerous devices have been employed to analyze or record the sound wave. We may mention the phonautograph of Leon Scott, spherical resonators, sensitive flames, diaphragms arranged to deflect a beam of light, diaphragms set up as part of an interferometer, motion of soap films, study of telephone currents by resonant circuits, oscillograph or string galvanometer and by microscopic examination or enlarged transcribing of phonograph records.

Following some of the theories as to the nature of speech offered as a result of these studies and also by independent cut-and-try methods, various attempts have been made to construct machines which under proper manipulation would talk or at least produce one or more of the speech vowel tones.

As regards the consonants, it is quite generally agreed that these are not properly sounds but merely different fashions of beginning or ending certain other sounds. The very name itself, *consonant*, indicates that it is something that goes along *with* the sound rather than being *sonant*, or a sound of itself. Of all the possible speech sounds, there are of course many which are neither definitely vowel nor consonant in character. Mr. Flowers quotes Helmholtz to this effect on the second page of his paper and as far as the consonants are concerned, his records and conclusions appear to be in agreement with the generally accepted view.

The theory of speech, however, about which there has been and still is a pronounced difference of opinion, relates to the vowel sounds and here opinion has been principally divided between what is called the " harmonic " theory and the " absolute pitch " theory.

According to the harmonic theory, one vowel is distinguished from another in the same way as are two different styles of organ pipes, by the number and relative magnitude of partials consisting of fundamental and harmonic over-tones. To demonstrate the correctness of this theory, elaborate sets of electrically operated tuning forks with associated resonators, for controlling intensity of sound sent out from each, have been constructed. Although a great range of tone quality can be produced with such a set of resonators, personally I have never witnessed the apparatus manipulated so as to produce anything fairly approaching a speech vowel. Nor could I produce any of the vowels from a more complete apparatus, consisting of a number of electrical generators in harmonic series with arrangements for controlling the intensity of each.

In the early analysis of speech, it was found that certain resonators responded readily to a given vowel tone, more or less irrespective of the pitch of a speaker's or singer's voice. This fact coupled with unsatisfactory results obtained from the series of harmonic forks, brought many adherents to the absolute pitch theory. If pitch alone were the essence of vowels, they should be heard frequently from a pipe-organ or from an orchestra. Such, however, is not the case. I have made phonograph tests (similar to that cited by Mr. Flowers) some years ago and agree with his conclusions on this point. Incidentally and as indicating the great caution which must be taken when using the phonograph to determine the essence of speech or study the quality of a sound, I may mention that Professor D. C. Miller several years ago, at the Cleveland meeting of the American Association for the Advancement of Science, operated a phonograph at normal and at reduced speed to show his audience that one vowel would change into another—in other words to show the correctness of the "fixed" or absolute pitch theory, the indentical experiment which Mr. Flowers cites to demonstrate the incorrectness of the same theory. The difficulty lies in too much psychology in proportion to the amount of physics. Having reason to doubt the sufficiency of either of the prevailing theories, or both in combination, I attempted to get at the root of the matter by observing and recording telephone currents with an oscillograph. The first of these records was taken in 1904 and the reproduction of a telephone current appearing on page 212 of Vol. XXIV of the A. I. E. E. TRANSACTIONS for 1905, is the earliest publication of such a record that I am aware of.

My records are not closely comparable to those in Mr. Flowers's paper for reason that he has limited his discussion to whispered sounds, whereas I gave attention principally to the sustained open vowels. Of these, the starting point is naturally the *A* (as in *far*.) This is the vowel which is produced by the voice mechanism with the muscles in the normal or relaxed position. It is the vowel on which the baby naturally cries, and it is extensively used in our vocabulary, as also in that of every other language. This sound however, does not appear among Mr. Flower's photographs nor in his alphabet of pattern pictures. This is because our alphabet is largely a series of arbitrary names for certain written or printed characters which in turn, in use may have any one of several different sounds. A more complete phonetic alphabet would have instead of 26 letters, approximately twice as many sounds of which, without going into the fine shades of pronunciation, some 14 or 15 would take the place of the present 5 character names for the open vowels.

I have previously described the sound *A* (as in far) as consisting of a series of relatively high frequency vibrations following a "curve of intensity." In the case of my own voice the vibrations proper come at the rate of 720 per second with an intensity cycle following a fairly definite curve at the rate of around 100 per second. The 720 cycles are subject to little or no control, while the 100

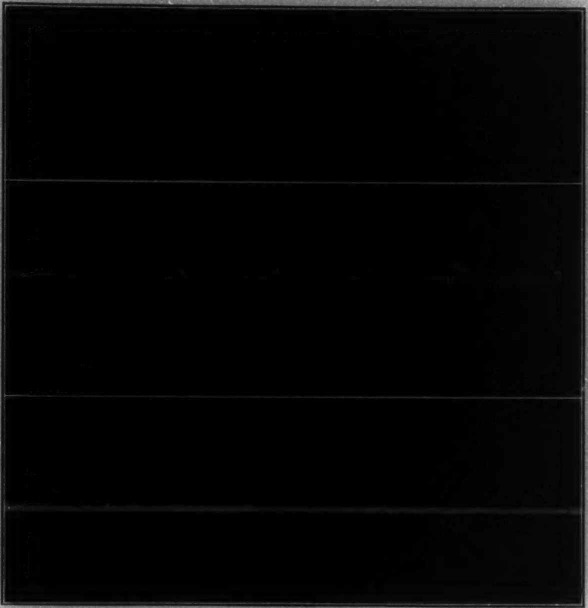


FIG. 3 [TAYLOR]

FIG. 4 [TAYLOR]

cycles (which is the *pitch* of the voice) may be lowered or raised to the pitch I may desire to speak or sing without materially changing the 720 cycles. Three typical oscillograph records with the voice differently pitched, are shown in Fig. 3 and 3a. If curves of this character are analyzed, as is frequently done by Fourier's series, the fundamental is practically absent and a long list of harmonics each with a particular phase relation is needed to approximate the record. Some experimenters have maintained that given a tuning fork for each of the harmonics shown by the analysis, that the vowel sound could be produced synthetically, but this I doubt unless special means were provided to secure also the definite phase relations indicated by the analysis. Furthermore, it appears probable that the 720-cycle vibrations are not always regularly continued from one intensity cycle to the next, so that the harmonic series of tuning forks could not be made to match the voice vibrations in this respect. The situation is analogous to the damped wave trains of spark telegraphy. The spark frequency may be 120 cycles per second (there being, however, no radiation of wave-length corresponding to this frequency), though the tone which is heard is of the spark frequency and the actual vibration frequency is not sensed. Other vowel sounds may be similarly though not so simply described. If the essence of the vowels is an intensity cycle recurring with a rapidity which we distinguish as the pitch of the note, it is evident that we have something here quite distinct from the harmonic theory or the absolute pitch theory.

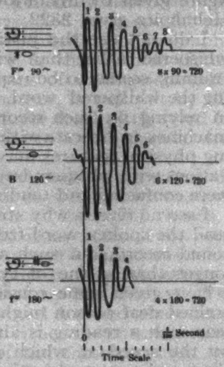


FIG. 3A—COMPARISON OF OSCILLOGRAMS OF VOWEL "A" AT THREE DIFFERENT PITCHES

I have regarded the "curve of intensity" as determined principally by the form of opening, and character of vibration at the vocal cords. Thus, in the case of the vowel *A* discussed, the opening is rather sudden and the closing gradual, which regulates the admission of air in such a manner as to cause the production of 720-cycle vibrations from throat, mouth or nasal cavities. In other words, the vocal cords are not the seat of the sound vibration but a throttle valve in a supply pipe. In this explanation, I differ from what Mr. Flowers offers where he speaks of the mouth and the behavior of the mouth muscles as producing his patterns in the case of a sustained vowel.

The best evidence which I have for my opinion rests on stroboscopic observations of my own vocal cords, pitching the voice to the period of intermittent illumination of the rotating stroboscope. Referring still to the vowel *A*, the vocal cords were seen to be vibrating at 120 cycles per second (the intensity frequency) instead of 720 cycles (the principal sound vibration frequency as disclosed by the oscillograph.)

The stability of the 720 cycles for my own voice on the vowel *A* might appear to lend support to the fixed pitch theory. However, at the same time and with the same apparatus with which these records were made, my wife's voice showed a characteristic 960 cycles for the same vowel. For this vowel Helmholtz assigns 1096 cycles. Also my records for the vowel *i* (as in pique, and more familiar in English as *ee*) Fig. 4, show pronounced vibrations at around 2000 cycles which is in fair agreement with the 2500 figure given by Mr. Flowers in his *ee* sounds. For this vowel Helmholtz gives 2322.

I do not see the justification for taking these records with whispered rather than with voiced sounds. While no special training seems to be required for whispering or for understanding the whispered word, perhaps too much is taken for granted in relying on such records as basis of design and construction of machines to operate with *voiced* words. The essential distinguishing physical features may not be the same. I made some observations with whispers but felt that the hissing and breath sounds were confusing and tending to conceal the essential data sought.

I see no reason why study and training may not enable one to read the spoken word from some form of photographic or other sound record, but such a record would have to be many times longer than a line of type corresponding to the same words. I have given some consideration to a visual device whereby a trained deaf person might see the word spoken by another, but fear such a reading is almost impossible of attainment, judged by the speed at which a printed page can be read. Similar time and space objections would appear to hold in a voice-operated machine of the type outlined by Mr. Flowers. If the paper cylinder rotates fast enough to make the consonants easily distinguished, the vowels and pauses will use up yards and yards for even moderate length sentences. Is there any marked saving in space, and why should his special form of record produced by resonant circuits, controlling mirrors and selenium cell, be as accurate or any more easily deciphered than a continuous record such as would be given by combination of telephone and oscillograph?

The problem is a fascinating one and Mr. Flowers is not the first to design devices nor to attempt the construction of apparatus. The earliest definite attempt in this line which has come to my notice, is that of Barlow about 1874. He called his device the "logograph" and arranged an India rubber diaphragm about 2¼ inches in diameter to draw a line on a moving strip of paper. Deflections of about ⅛ inch were obtained as the apparatus was arranged. See *Journal of the Society of Telegraph Engineers* (England, vol. VII, 1878, page 65).

John B. Flowers: Many interesting and valuable suggestions have been added to my paper on "The True Nature of Speech," and I have considered them all with deep interest. To answer them fully and with the hope that the reply would be conclusive and definite, is not possible until after the completion of the voice-operated phonographic alphabet writing machine. With a set of pattern pictures of the speech sounds as produced by this machine, it will be possible to definitely establish such important points as were brought up by Dr. Williams and Mr. Chubb, that certain of the vowel sounds may be pattern pictures or low-frequency beats produced by combining resonance tones of nearly the same pitch. I note with satisfaction that the main idea of the paper is pretty generally accepted, viz., that the speech sounds are each represented by a special pattern or form picture as shown in the table called the phonographic alphabet. How absolutely necessary it is that a form picture of the sound wave should be the means of distinguishing the different alphabet sounds one from another, is well put by Mr. Taylor, when he explains that, if a definite fixed pitch stood for an alphabet sound we should often hear the speech sounds when listening to an orchestra.

In reply to Mr. Taylor's interesting statement regarding the formation of the vowel sounds as being determined by the form of opening, and character of vibration of the vocal chords, I have personally learned by stroboscopic observation of the vocal chords of several persons by the assistance of a throat specialist, that the vocal chords are absolutely quiet during the *whispered* vowel A (as in far), the same vowel tried by Mr. Taylor. This then proves that the formation of the vowel A sound is not determined by the vocal chords but is due to either the natural coming together of certain resonance tones of the throat, mouth, and nasal cavities, thus forming low-frequency patterns or beats, or is an intensity variation controlled by the muscles of the lungs, throat and mouth, utilizing a muscle tremor. In this connection, it is important to note that the muscles of the human diaphragm and lungs are mainly controlled by the phrenic nerve and are operated by nerve impulses varying between 30 and 100 cycles per second. The inference can be drawn that when the air is expelled from the lungs by the diaphragm muscle in forming a vowel sound, it comes out in intensity pulses of a definite shape and period corresponding to that of the nerve impulse. I am quite sure that this is the explanation for the intensity variation of such a simple sine wave curve as that of the alphabet sound O, curve No. 17.

In answer to the query why the special record obtained by the voice-operated machine of my design would be more condensed and more easily deciphered than a combination of telephone and oscillograph, I submit the following illustration. Assume that the word *boat* is spoken and it is to be recorded in the phonographic alphabet. This is the phonetic word bōt. The time required for utterance is (for ordinary speech) approximately b in 1/50 second, o in 1/4 second, and t in 1/25th second. Let the cylinder of paper for the record rotate at a speed of 3 inches per second; then the pattern b is 1/16th of an inch long, o is 12/16ths of an inch long, and t is 2/16ths of an inch long. The resulting record occupying a space 15/16th inches long in contrast to that of the typed distance of 9/32 inches. Therefore, the record of the voice-operated machine will be 3 1/3 times the length of the corresponding letters if typed. It is evident that the combination of telephone and oscillograph only writes down the compound speech curve *without analyzing* it into its elements and the resulting record has been found so complex owing to the compounding of different tones and their variations in intensity, that it is practically impossible to decipher it. But the voice-operated machine would have the power of writing down in the form of the phonographic alphabet the variations in intensity of any of the speech-tones which operate the resonating elements of the machine *after analyzing* the compound speech curve into the tones of which it is composed.

Presented at a section meeting of the American Institute of Electrical Engineers, Denver, Colo., February 19, 1916.

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THE FUTURE OF WATER POWER IN THE UNITED STATES

BY CHARLES W. COMSTOCK

Abstract of Paper

This paper gives a careful compilation of figures showing the total fixed installed primary power in the United States and similar figures for total installed water power, at the same time calling attention to the unreliability of statistics in general. With these figures, those compiled by the Commissioner of Corporations are summarized and compared.

The geographic distribution of installed water power is considered and many interesting facts revealed when these figures are examined from the viewpoint of population distribution. A study of the development of water power between 1889 and 1909 shows some interesting differences as compared with distribution of manufacturing power and total developed water power.

The author next takes up the question of the possibilities of water power development and points out the fallacy of power development waiting upon demand instead of creating it. The immense field for hydroelectric power which a development of the electro-chemical and electro-metallurgical industries would create with the success of such industries abroad is cited and an appeal made for a Federal policy of encouraging business enterprise instead of obstructing it.

In presenting this paper before an organization of electrical engineers, I wish to say by way of preface that it is not electrical, nor yet engineering. It is, if anything, economic; in some degree comparative, and slightly statistical. Having in mind Disraeli's classification of untruths as "lies, damned lies, and statistics," you may know what to expect.

In order to get ourselves properly oriented, as the surveyors say, it is well to take a bird's-eye view of the entire power field. The total fixed installed primary power in the United States, as given by the Census Bureau, is as follows:

The unit is the horse power.

Commercial and municipal central electric stations, 1912	7,528,648
Street and electric railways, 1912	3,665,051
Steam road electrification, 1912	193,956
Total electric installations	11,387,655
Manufacturing, 1909	16,802,706
Mines and quarries, 1909	4,402,554
Total fixed installed primary power	32,592,915

The Census Bureau has a disconcerting practise of collecting some of its data as of the years ending with two and seven, while other information is gathered for the years ending with four and nine. Our figures are, therefore, out of phase, the electric power data leading by 216 degrees, and we are not strictly within our rights in making these numerical additions, but the results will serve our purposes for general comparisons.

The figures here given for manufacturing and for mines and quarries are exclusive of nearly two million horse power classed as rented power, which is included under the central electric stations. No account is taken of the power installed in isolated plants, such as hotels, large mercantile establishments, office buildings and the like. The aggregate of these must be very large, but they have not been included in census returns, and no list of them is believed to exist.

In addition to the fixed power, consideration must be given to the power generated by steam locomotives. There are in the United States about 65,000 locomotives in service. It would be absolutely meaningless to add their rated horse power, even if it were obtainable. Doubtless it exceeds the total fixed power of the country. We can, however, by an indirect method, approximate its equivalent in fixed power. In the year ending June 30, 1914, the railroads of the country expended, in round numbers, $242,000,000 for locomotive fuel. A small portion of this fuel was oil, but far the larger part was soft coal. If the average price of this coal be assumed at $2.00 per ton, the locomotives burned 121,000,000 tons (1 long ton = 1.01 metric ton) of coal during the year. Allowing 26 tons per h.p-year (about six pounds (2.7 kg.) per h.p-hr.), the equivalent continuous output is 4,692,000 h.p., or, with a 60 per cent load factor, 7,820,000 h.p. If all the railroads in the country were electrified, the necessary installed power for their operation would probably not be far from this latter figure, although, of course, the total coal consumption would not exceed one-third that used under the present system. The fixed installation, in these circumstances, would then be about 120 h.p. per locomotive in service.

The data are not available with which to estimate the power used in navigation, and the inquiry would not be pertinent in this connection, even if we could make the estimate.

We have, then, at the present time in the United States the equivalent of at least forty million horse power in fixed installations, without counting the isolated plants already mentioned, which must total a very large amount, though we have no basis for an intelligent guess.

How much of this is water power? From the census reports again, we have the following:

Commercial and municipal central electric stations, 1912	2,471,081	h.p.
Street and electric railways, 1912	471,307	"
Steam road electrification, 1912	8,000	"
Total hydroelectric installations	2,950,388	"
Manufacturing, 1909	1,822,888	"
Mines and quarries, 1909	97,460	"
Total installed water power	4,870,736	"

The installed water power is, therefore, 14.94 per cent of the total fixed primary power, or about 12 per cent of all power, including locomotives.

In 1908 the Census Bureau reported to the National Conservation Commission that the developed water power of the country aggregated 5,356,680 h.p., of which 3,396,103 h.p. represented developments not less than 1000 h.p., and 1,960,577 h.p. were smaller developments. These figures, however, were not limited to actual installations, but included many power sites only partially developed, or, to quote exactly, "undeveloped power sites upon which some expenditure had been made."

In a report to the Secretary of Commerce and Labor, dated March 14, 1912, the Commissioner of Corporations stated the developed water power in plants of 1000 h.p. or more, to be 4,016,127 h.p. of which 2,961,549 was classed as commercial and 1,054,578 as manufacturing. These figures are of date June, 1911. The difference of nearly 800,000 h.p. between this estimate of manufacturing power and the census figures of 1909 is probably to be accounted for by small manufacturing plants. To the figures above given, the Commissioner adds 2,000,000 for plants of less than 1000 h.p., making "a grand total, in round numbers, of at least 6,000,000 h.p. as the total water power of the United States, developed and under construction in June, 1911."

A still further addition of 2,638,528 h.p. is made by the Commissioner to cover "the undeveloped power owned or controlled by the concerns reporting developed power." This report of the Commissioner of Corporations may be summarized as follows:

Concerns having 1000 h.p. or more:

Commercial	2,961,549 h.p.
Manufacturing	1,054,578 "
Undeveloped	2,638,528 "
Total	6,654,655 "
Plants of less than 1000 h.p., about	2,000,000 "
Grand Total	8,654,655 "

This appears to be the only basis for the inaccurate statement made by Mr. George Otis Smith, Director United States Geological Survey, in an address delivered before the Second Pan-American Scientific Congress, on December 28, 1915, that "the present installation of water-power plants in the United States is estimated at 8,500,000 h.p." There is an obvious difference between an installed plant and the mere ownership or control of a site. I know of several power sites whose owners are looking anxiously for someone to help them let go of the bear's tail. No doubt it was such misuse of data that prompted Disraeli to place statistics in the next place beyond the damned lie.

Taking into account the fixed power equivalent of steam locomotives, and the certainly large, though unknown, amount of power in isolated plants, it is probably safe to say that the actual water power installations of the United States aggregate not far from 10 per cent of the total installed primary power.

The next point of interest is the geographic distribution of the installed water power. This is shown in the following table:

GEOGRAPHIC DISTRIBUTION OF WATER POWER

	Manufacturing, 1909	Central electric stations, 1912	Electric railways 1912	Total
	%	%	%	%
New England	41.5	7.4	7.4	20.9
Middle Atlantic	25.7	26.8	4.1	24.0
East North Central	11.4	10.0	8.9	10.8
West North Central	4.8	4.1	4.7	4.3
South Atlantic	10.1	14.1	13.6	12.4
East South Central	1.6	1.5	0	1.3
West South Central	0.2	0.2	0	0.2
Mountain	1.2	12.9	4.5	7.4
Pacific	3.5	23.0	56.8	18.7
	100.0	100.0	100.0	100.0

The distribution of the power used in mining and quarrying could not be learned, but the total quantity so consumed is small, and, whatever its distribution, can not sensibly affect these figures.

An examination of this table reveals several interesting facts. One-half the population of the United States is east of the western boundary of Ohio; sixty per cent of the developed water power is east of that meridian. One-half the population is north of the parallel of Denver; seventy-five per cent of the developed water power is north of the same line.

The Atlantic coast states, from Maine to Florida, contain 57 per cent of the developed water power and 41.3 per cent of the population. The states west of the eastern boundaries of New Mexico, Colorado, Wyoming, and Montana contain 26 per cent of the developed water power and 7.5 per cent of the population. The great Mississippi valley region, from Canada to the Gulf of Mexico and from Pennsylvania to Colorado, contains rather less than 17 per cent of the developed water power, with 51.2 per cent of the population. The three Pacific coast states alone contain 18.7 per cent of the developed water power, but only 4.6 per cent of the population.

As we shall see later, all this has a bearing on the alarmist talk about water power monopoly with which we are regaled from time to time by Young-man-afraid-of-his-job or some other member of a Federal bureau, the sole purpose of whose existence is to seek out the unfortunate private citizen who has more than three dollars, and regulate him. With these gentry it is a case of "Johnny, go out and see what Willie is doing, and tell him to stop it."

The general character of the evolution in the development and use of water power is familiar to all. The first water wheels were installed to drive grist mills, saw mills and other plants whose activities were directly connected with the every-day necessities of the people. Naturally these were in the New England states. As the population increased and its requirements became less primitive, the power sites were further developed and applied to paper manufacture, the textile industries and the like. Even today 41.5 per cent of the water power devoted to manufacturing, as distinguished from that generated in central stations and sold for general commercial purposes, is located in New England, and 67.2 per cent is in New England, New York, New Jersey and Pennsylvania. Nearly all the remainder is in the South Atlantic states and in the states north of the Ohio and east of the Mississippi river.

The water power thus directly applied to manufacturing industries has not increased very rapidly for the past twenty years, and the growth is likely to be even less important in the future. In 1889 the water power so applied aggregated 1,255,045 h.p.; in 1899—1,454,112 h.p.; in 1909—1,822,888 h.p. The increase was thus 15.9 per cent from 1889 to 1899, 25.4 per cent from 1899 to 1909, and 45.2 per cent from 1889 to 1909. For the same periods the total power used in manufacturing increased from 5,938,635 h.p. in 1889 to 10,097,893 in 1899, or 70 per cent and to 18,675,376 h.p. in 1909, an increase of 85 per cent since 1899, and of 214 per cent since 1889.

The North Atlantic states became important manufacturing centers because of readily accessible and easily developed water powers. Large populations grew up around them and these people in turn constituted a market for the manufactured products. Thus, this region had three of the four requisites for a successful manufacturing country, viz: cheap power, ample labor, and a near-by market. These advantages it still has to a considerable extent, though the first it is rapidly losing.

In the early nineties, hydroelectric development began in earnest. The first Niagara plant (55,000 h.p.) about 1894, was the first important installation of this character. In 1902 the aggregate of the hydroelectric developments of the United States was 438,472 h.p. in central station installations, and 49,153 h.p. in electric railway plants, a total of 487,625 h.p. In 1907 these had increased to 1,349,087 h.p. in central stations, and 91,961 h.p. in electric railway plants, a total of 1,441,048 h.p. or nearly as much as the total installed water power for manufacturing purposes. In 1912 the central station installations had become 2,471,081 h.p. and the electric railway plants 471,307, h.p. a total of 2,942,388 h.p., or 61 per cent more than all the installed manufacturing water power. The increase in hydroelectric installations was 195.5 per cent from 1902 to 1907, 104.2 per cent from 1907 to 1912, and 502 per cent from 1902 to 1912. The proportionate increase in ten years, ending 1912, was more than eleven times the proportionate increase in manufacturing water power in twenty years ending 1909.

A study of the distribution of the development shows some interesting differences as compared with the distribution of manufacturing power and of total developed water power.

New England has only about 8 per cent of the hydroelectric as against more than 40 per cent of the manufacturing power. The North Atlantic states, including New England, have about 30 per cent of the hydroelectric and nearly 70 per cent of the manufacturing power. The eastern half of the population has only 45 per cent of the hydroelectric with 60 per cent of the total developed water power. The northern half of the population has about 70 per cent of the hydroelectric development.

The Atlantic coast states have 45 per cent of the hydroelectric development, and a little more than 41 per cent of the population. The states between Pennsylvania and Colorado have more than one-half the population, but only 16 per cent of the hydroelectric power. The states from Colorado west have only 7.5 per cent of the population, but 39 per cent of the hydroelectric development.

These apparent anomalies are not difficult to explain. Falling water is a source of power, but we must have fall as well as water. In the Appalachian region there is ample water and moderate fall. In the Mississippi valley the fall is slight and difficult to utilize, except in rare instances. From the Rocky mountains to the Pacific we have plenty of fall, but are frequently short of water. In the immediate vicinity of the Sierra Nevadas there is an abundance of water and many falls which can be utilized at moderate cost.

The Pacific coast states, without coal, and until the development of the southern California oil fields, without fuel of any kind, were quick to grasp their opportunites. What was done in other parts of the country by means of fuel, they hastened to do with the "white coal". Thus, we see that the proportion of the total central station power, which is generated by water, is much greater in the far west than elsewhere. This appears from the following table:

PERCENTAGE OF TOTAL CENTRAL STATION POWER
GENERATED BY WATER

New England	21.1
Middle Atlantic	22.2
East North Central	12.2
West North Central	14.3
South Atlantic	40.4
East South Central	10.6
West South Central	2.5
Mountain	64.8
Pacific	58.6

The three Pacific coast states, with 4.6 per cent of the population, have 12.3 per cent of all the central station power in the United States. Of this, nearly 60 per cent or 7.2 per cent of all central station power in the country is hydroelectric.

Now, what are the possibilities? In Water Supply Paper 234, United States Geological Survey, Mr. M. O. Leighton gives some estimates of the potential water power of the United States. Although his paper is entitled "Undeveloped Water Powers," his estimates appear to cover the total water power possibilities, without regard to what portions have already been developed. The paper was published in 1909, and the estimates probably correspond to the data at hand in 1908. The state of Pennsylvania is expressly excluded as information was not available to permit an estimate for that state. Two estimates were made—one, regarded as the absolute minimum, based on the stream discharge "for the lowest two consecutive seven-day periods in each year;" the other, described as "assumed maximum," being the quantity which could be generated during six months in the year. Neither estimate takes any account of storage.

The first is stated as 36,916,250 h.p., and the second as 66,518,500 h.p. Mr. Leighton estimates further that, by the use of all practicable storage sites, the grand total of possible water power development in the United States will be at least 200,000,000 h.p.

These estimates include a minimum of 5,800,000 h.p. and "assumed maximum" of 6,500,000 h.p. for the Niagara river. Under present treaty provisions, not more than 25 per cent of the possible power at Niagara falls can be developed, and of this the United States is entitled to only about 36 per cent.

In 1912 the Commissioner of Corporations revised Mr. Leighton's estimates by making the above correction for the Niagara river, adding 331,000 h.p. for Pennsylvania, and 117,750 h.p. for some other changes, and cutting one-sixth off the whole thing for good measure, arriving finally at the following figures:

	Minimum h.p.	Assumed maximum h.p.
North Atlantic	2,225,000	4,092,000
South Atlantic	2,344,000	4,256.000
North Central	1,733,000	3,558,000
South Central	1,438,000	2,785,000
Western	18,996,000	36,707,000
United States	26,736,000	51,398,000

The Commissioner refused to consider the possibility of greater development by storage. He says: "Any estimate including storage, therefore, must be mainly theoretical." Just what he means is not clear, but his purpose in omitting an important element in power development is obvious.

The above figures are not particularly reliable. They are largely speculative, and are based on very meagre data and grossly inadequate surveys. Moreover, the motive underlying the estimates of the Commissioner of Corporations was not honest. However, we may accept them, tentatively, and see to what conclusions they will lead us.

The following table gives the installed water powers side by side with the minimum potential power as estimated by the Commissioner of Corporations:

	Minimum potential power	Installed power
North Atlantic	2,225,000 h.p.	2,134,000 h.p.
South Atlantic	2,344,000 "	589,000 "
North Central	1,733,000 "	729,000 "
South Central	1,438,000 "	79,000 "
Western	18,996,000 "	1,229,000 "
United States	26,736,000 "	4,760,000 "

It appears from this table that the North Atlantic states have practically exhausted all their available water power, notwithstanding the Niagara developments aggregate only about 270,000 h.p. on the American side, instead of the 518,000 h.p. included in the Commissioner's estimate. The South Atlantic states still have a possible 2,000,000 h.p., and the Central states about 2,000,000 h.p. more, but nearly all the water power possibilities of the future are west of the eastern boundary of Colorado, where there yet remains, even by the minimum estimate, and with no allowance for storage, nearly 18,000,000 h.p. undeveloped. On the basis of the "assumed maximum," the undeveloped possible water power in the western states exceeds 35,000,000 h.p. What this would be if storage possibilities were considered, I do not know.

The three Pacific coast states alone contain about 45 per cent of the potential water power of the country. Their aggregate present development is about 880,000 h.p., leaving possibilities from a minimum of 10,524,000 h.p. to an "assumed maximum" of 22,298,000 h.p. without considering storage.

The "assumed maximum" of potential water power, as estimated by the Commissioner of Corporations, is rather in excess of the present total installed primary power of the United States, including the equivalent of the steam locomotives now in service. This, however, is not to say that if all of this water power were now installed, the steam plants would cease to operate. Seventy per cent of the possible water power is in the western one-third of the country, with 7 per cent of the people. No matter what the population may become numerically, it is probable that fully one-half will always, as now, live in the great Mississippi basin, for this is the region best adapted to the production of the staples of agriculture and animal husbandry. We are not justified in anticipating such improvement in the art of transmission as will permit the use along the Missouri river of power generated in the Mountain and Pacific states. I do not know the longest transmission line now in operation—someone is always going his predecessors one better—but probably the 238-mile (383.02-km.) line of the Southern Sierras Company is the limit of present practise. Let us suppose that power might be transmitted 500 miles (804.6 km.) with a reasonable loss. A belt 500 miles wide with the summit of the Sierra Nevadas as its western limit would have as its eastern boundary a line passing near Great Falls, Montana, Pocatello, Idaho, across the western edge of Great Salt Lake, crossing about the middle of the southern boundary of Utah, and near Gallup and Silver City, New Mexico. Clearly, no conceivable development in that belt of country would ever call for the use of 10,000,000 to 22,000,000 h.p. How would you like to be the grinding monopoly to own all these power sites and pay taxes on them until such time as you might develop them with a reasonable chance to earn more than their fixed charges and cost of operation? This is the "bogie man" with which our conservation friends are trying to frighten us.

What is to become of all this power if it shall ever be developed? The present fixed installed primary power of the United States, including steam locomotives, is between four-tenths and five-tenths of a horse power per capita. On this basis the minimum potential water power in the Pacific coast states alone would provide for a population of twenty to twenty-five million people west of Great Salt Lake. What would they do? They would be much in the position of the Irish woman and the Chinaman who were ship-wrecked on a desert island—they made money doing each other's washing.

Every important hydroelectric enterprise from the first Niagara installation to the Keokuk plant, has been financed on the basis of an existing market for at least a part of the output. No responsible banking house will listen to a power scheme which can not show a market in sight sufficient to pay fixed charges. The Niagara Falls Power Company was financed on the power consumption in Buffalo and other nearby cities. The Standard Electric and the Bay Counties Power Company, as well as other properties now belonging to the Pacific Gas and Electric Corporation, had their markets in sight around San Francisco bay. Snoqualmie Falls had Seattle, Tacoma and the entire Puget Sound district. The McCall Ferry plant is only seventy miles (120.7 km.) from Philadelphia, and the Mississippi River Power Company had a 60,000 h.p. contract with St. Louis before work was begun at Keokuk.

So it has been with all of them, but it can not continue to be if anything like the enormous quantities of power above mentioned are to be developed within limited areas. We must go back to something like the methods of early New England days. We must choose those industries in which power is the all-important element, locate them within transmission distance of the power sites, and then finance the industries by virtue of their own strength, regarding the power merely as an adjunct. This is in strong contrast with the method of building a power plant and then waiting for someone else to build the factories and buy the power.

Up to this time our power development has always followed a demand instead of seeking to create it. This has not been so generally true elsewhere, nor have we followed the same method in other activities. The Union Pacific railroad would be nonexistent today if its promoters had waited for the Indians to petition Washington for improved transportation facilities. The coal range would still be in universal use if the gas range had not been put on the market until the housewives clamored for it.

In the United States most of our power has been used to meet the every-day demands for light, heat, transportation and the operation of such industries as are incidental to city life. Outside of Niagara Falls, we have not developed any electro-chemical or electro-metallurgical industries worthy the name. Abroad it has been quite different. The Norwegian Nitrogen Company, for example, located its plants near the power sites, developed power, not as an end in itself, but as an adjunct only, and built up an enormous industry where before there had been nothing. In 1913 it had in operation 260,000 h.p. used solely for the fixation of atmospheric nitrogen, and had planned the development of 280,000 additional h.p. The furnace and process by which this is done were not invented until 1903.

In 1910 there were in the French Alps operating water-power plants aggregating 475,000 h.p., 80,000 h.p. more under construction, and 700,000 h.p. projected. Of the power produced at that time, 210,000 h.p. was consumed in electro-metallurgical work and 60,000 h.p. in electro-chemical industries. These made up 57 per cent of the total. Of the remainder, 30,000 h.p. was used in the paper and wood industries, and 165,000 h.p. for commercial power, light and traction. The distribution of this power among the industries is significant.

It has often been said that fixation of atmospheric nitrogen is not practicable in the United States because of the high cost of power. Let us look into this briefly. Nitrate of soda costs $70.00 per ton (1 long ton = 1.01 metric ton) in New York. This is equivalent to $95.00 per ton for pure nitric acid. The operations in Norway and elsewhere produce about 500 kg. (1,102.3 lb.) of nitric acid per kw-yr., or 1.82 kw-yr. per ton of acid.

The Mississippi River Power Company supplies power to St. Louis at $24.00 per kw-yr. at 60 per cent load factor. At this rate the power necessary to produce one ton of nitric acid would cost about $44.00. The margin between this and a selling price of $95.00 is sufficient to warrant a very careful inquiry before accepting the statement that "it can not be done."

The greater part of the hydroelectric power in the French Alps devoted to electro-metallurgical work, is used for the manufacture of special alloys, such as ferro-tungsten, ferro-molybdenum, ferro-titanium, etc. The Paul Girod works alone produce more than two million dollars worth of these alloys annually. The western part of the United States is as well supplied with the raw materials for such manufacture as any part of the world.

In northern California the production of pig iron in the electric furnace was inaugurated about six years ago. This experiment has been attended with considerable technical successs though with what commercial results I am not advised. Doubtless that and similar enterprises elsewhere will ultimately succeed. When they shall do so, their demand for power will be very large.

Such and many other industrial undertakings will grow up in the western part of the United States when a Federal policy of encouraging business enterprise and initiative shall take the place of the present obstructive tactics whose justification is attempted on the ground that someone may corner 22,000,000 h.p. in water falls, and that the world would then freeze to death in about five thousand years. When that freezing takes place, certain Federal bureaus and officials will not be suffering from the cold.

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IRON LOSSES IN DIRECT-CURRENT MACHINES

BY B. G. LAMME

ABSTRACT OF PAPER

The term *iron loss*, as used in connection with rotating machinery, is shown to cover a large number of losses, some of which actually do not lie in the iron itself. The term *core loss* should be used except when the losses are actually located in the iron itself. It is shown that no great accuracy is practicable in the calculation of the actual iron losses, except in special instances, due to the fact that the ordinary treatment of materials in manufacture is such that large discrepancies are almost sure to occur, in certain types of apparatus. A brief explanation of several causes of variation in losses is given.

In the treatment of core losses in direct-current machines, the four principal sources of losses are considered, namely—armature ring loss, armature tooth loss, eddy currents in buried conductors, and pole face losses. Under eddy current losses is given an explanation of certain losses not usually taken into account, and a crude method of calculation is given, with some tabulated results.

Under pole face losses an empirical formula is given, also some tabulated results.

The effect of load on losses is discussed, but no calculated results are given. Some of the effects of flux distortion on the losses are shown.

A principal object of the paper is to show the impracticability of calculating all the core losses with any great accuracy at no-load, and the still greater difficulty in predetermining them with load.

IRON LOSS is a general term to cover a number of losses,, of various kinds, which, by the nature of the tests, are included in one set of measurements and which, in reality should be known as core loss. The term has been used so promiscuously, without indicating what it really includes, that many have come to believe that it means the true iron loss and nothing else. In fact, however, the true iron loss, in many cases, may be only a moderate percentage of the core loss. Usually no distinction has been made between losses simply located in the iron, and those due to the magnetic conditions in the material itself. The readily practicable methods of measuring the core losses show only their sum and there is no true indication of the relative values of the various components. To separate the total core loss into its various components, except by complicated and expensive laboratory methods, appears to be almost impossible. However, it is possible to indicate the various components and their probable causes, and in some cases they can be segregated very crudely by calculation.

In most rotating machinery the calculation of the individual elements, which make up the total core loss, is necessarily only approximate, in commercial apparatus. This is due partly to the fact that there are many possibilities of variation in loss on account of conditions of manufacture and materials, as will be described later. This is evidenced by the fact that two machines, built at different times from the same drawings and the same tested grade of materials, will ofttimes show materially different core losses. If two such machines vary twenty per cent from each other in core loss, it is obviously impracticable to expect any refinement in calculation closer than twenty per cent. Even if we always could come within twenty per cent by direct calculation and could place any great reliance upon the results, it would be a great step ahead, in certain types of apparatus. In the discussion of the various losses and their causes, given throughout the following paper, it will be shown why it is impracticable to calculate, with any exactness, certain of these losses.

In separating the total core loss into its components, two principal classifications of losses may be made. One of these is eddy current loss, either in the iron laminations themselves or in other conducting parts wherein e.m.fs. are generated during rotation. Such e.m.fs. will set up local currents where closed paths are possible, and if such paths are in the laminations themselves, instead of in neighboring solid parts, it is simply incidental. Eddy current loss in the laminations is, therefore, not a special kind of loss, and it should rightly be classed with other eddy losses in the machine.

The second class of losses includes those due to changes in the magnetic conditions in the iron itself; these are known as hysteresis losses. These latter are dependent upon the material itself and not its structure. Lamination is primarily for increasing the resistance in the eddy current paths and not for the purpose of affecting the hysteresis. In fact, lamination may increase the hysteretic losses, for a given volume of material.

The principal object of this paper is to show causes for some of the principal losses. These are usually related to two sets of frequencies, namely, the normal frequency (revolutions per second times number of pairs of poles), and some very high frequency, dependent upon the number of slots, commutator bars, etc. The hysteretic losses are undoubtedly affected by these higher frequencies but apparently not to the same extent as the eddy losses. These high-frequency losses are liable to be present in most classes of rotating machines, while in some instances they may overshadow all other losses. Certain of them are characteristic of certain types of machines only, while others are liable to be present in any type of rotating machine.

In most classes of rotating machines, only the no-load core losses can be measured with any accuracy by ordinarily convenient methods of measurement. However, if the various components of the no-load loss can be approximately determined, then it is possible to indicate in what way these same components will be affected by load. A quantitative determination of the component losses with load is, however, very difficult to determine except in a very few classes of machines.

In direct-current machines the principal no-load armature core losses are the hysteresis loss in the iron, eddy losses in the iron and copper, and eddy losses in other adjacent conducting parts, which may be seats of e.m.fs. The relative values of these losses are dependent upon many conditions. In a thoroughly well designed machine the eddy losses in the copper and any other parts than the iron should be relatively small compared with the iron loss proper. Again, the proportion of hysteresis to eddy loss in the iron itself depends upon many conditions, such as the various frequencies in the machine, the grade of material, the degree of lamination, the perfection of the insulation of the laminae from each other, the distortion of the material in handling and building, the conditions of punching, treatment during assembly, grinding, filing, etc. Here, at once, so many variables appear that one cannot reasonably expect any great accuracy in any predetermination of eddy loss in the iron itself. Hysteresis loss is also affected by some of these conditions.

It is a fact well known to designers that the iron loss tables used by transformer engineers do not directly apply to rotating machinery, but that an increase, in some cases, of one hundred per cent or more is necessary, depending upon the type of machine. This increase is due largely to additional causes of loss which do not occur to any appreciable extent in transformers. Some of these additional losses are as follows:

(a) Handling of iron. Experience shows that well annealed armature iron will have its losses very materially increased by springing or bending. If a lamination is given a decided bend, beyond the elastic limit, and then is straightened out, the loss at the part which has been bent may be increased as much as 100 per cent. This fact must be taken into account in machinery where armatures with many light teeth are used. Here it is almost impossible to prevent some abuse of the iron, especially in the teeth, which are the parts usually worked the hardest. Furthermore, tests have shown that if iron is bent, even at a small angle, and not beyond the elastic limit, the loss is materially higher with the iron in this strained condition, although the loss may return to normal when the iron is allowed to spring back to normal position. And if the iron is annealed in a curved or warped position, then when straightened out in building the strain is present, with increased loss. In building up armature cores, undoubtedly part of the iron is put under stress, especially in the teeth. Any dent in the iron, produced by hammering or otherwise, also tends to increase the loss.

(b) A second source of increased loss in the iron is due to the operation of punching. In shearing the iron a small amount adjacent to the sheared part is affected much in the same way as when iron is bent beyond the elastic limit. In transformer plates this strip next to the sheared edge represents but a very small percentage of the total volume of each plate or lamination. However, in armatures with many comparatively long narrow teeth, this sheared part may represent a relatively large percentage of the whole plate and, moreover, this is a part which often has the largest losses. But this may not have as great effect on the losses as another result of the shearing, namely, the sharp burrs which are left on the iron. These may be very small or almost negligible in appearance and yet represent quite a large percentage of the thickness of the plate. For example, a burr of two mils height, or 1/500 in., seems to be very small indeed, and yet it is about 12 per cent of the thickness of a 17-mil lamination. Dies must be maintained in very good condition to keep the burr below two mils. The effect of this burr is to bring increased thickness and pressure at the edge of the sheets, particularly at the teeth. If the laminations are all turned one direction in building and the edges match perfectly the sheets might fit together so accurately that the burr would cause no extra thickness. But it is impossible to obtain such accuracy in practise and, therefore, the burrs of one sheet "ride" upon the surface of the next sheet, thus increasing the total thickness of the built-up iron. In practise, however, the iron is pressed down to approximately uniform height throughout. This means that the burrs carry considerable of the pressure at the armature teeth and there is more or less of a tendency to cut through the insulating film on the plates, thus increasing the eddy current losses. This is obviously a variable condition depending upon the accuracy of building, upon the condition of the dies, etc., and no method of calculation can take this loss into account with any accuracy. In small machines with low voltage per unit length of core, this loss usually is not of great importance. However, in high-speed large-capacity machines, it becomes increasingly important and in some cases special means are used for removing the burr before insulating the individual armature plates.

(c) Another source of iron loss, and one which also is beyond the scope of calculation, is found in the filing of armature slots and cores. In ideal armatures with perfect punchings and assembly, there should be no occasion for filing. However, the practise, in many cases where the armature iron does not build up with perfectly smooth surfaces in the slots, is for a limited amount of filing to be done. Usually this takes off only isolated high spots, so that the adjacent laminations are not bridged over to any great extent by the burrs due to filing. The tendency of most workmen is to file down to a nicely polished surface, whereas a coarse filing gives better results as it tends to break the laminations away from each other. Filing is most harmful in machines having a relatively high voltage per unit length of core. A milling cutter for cleaning out slots is usually worse than a file, as it produces greater burring of the edges. However, if the milling is followed by filing with a very coarse file the results may be just as satisfactory as with filing alone. Obviously, no method of calculation can show accurately the losses due to such burring.

(d) The iron losses are affected to a certain extent by pressure, that is, by the tightness with which the core is clamped.

The loss due to this is probably closely related to some of the preceding losses, such as bending and springing of plates, effect of burrs, etc. In small machines the effect of pressure apparently is of little moment, but in large very long cores it may become very appreciable. It is particularly noticeable in large turbo-generator armatures where the cores are very wide. In such machines, in attempting to draw the core down to a sufficiently solid condition as a whole, the parts next to the end plates are liable to receive abnormal pressure, with consequent increase of loss in those parts. For this reason, it is the practise in some cases to add an extra separation of paper at frequent intervals near each end of the core. Experience shows that this equalizes the losses and temperatures very materially. That this is due to undue pressure and not to stray field or other conditions, is indicated by the fact that when high temperatures are found in the iron, at each end of the core, very often the condition can be relieved by simply lessening the pressure to a comparatively small extent. The writer has known cases where the temperature in the end sections of the iron has been reduced 30 to 50 per cent by "easing off" the end plates. The total loss in the core may not be reduced very much, for the reduction in pressure usually affects only the end sections to any great extent. Presumably this loss is due to increased contact between the adjacent plates, possibly from the burr, but not entirely so, for similar results have been found in some cases where the burr had been fairly well removed before enameling the plates. The character of the enamel coating used for insulating purposes also has something to do with this.

In connection with pressure, the effect of heating of the core may be considered. Cases have been noted where the effect of high temperature of the core has been to increase the pressure between the laminations, due to expansion. This in turn increased the loss and thus still further increased the temperature. This effect has not been uncommon, to a minor extent, but a few cases have occurred where the combined pressure and temperature cumulatively have resulted in excessive core temperatures. In one case which the writer has in mind, a certain large machine operated for about two years without any noticeably high temperature in the core. Then, in a comparatively brief time, it showed evidence of increasing temperature until finally an entirely prohibitive temperature showed at one place. Examination showed that the core was very tight and all evidence indicated that increased temperature was causing increased pressure and thus further increasing the loss. In this machine, fortunately, the construction of the armature core and winding was such that the end plates could be released very easily about ¼ in. on each end. This was tried as an experiment and the temperatures all returned to the former normal of about 30 deg. cent. rise. As an interesting side issue, it may be mentioned that on this machine the armature teeth at each end of the core had been breaking off, although stout brass supporting fingers had been used. Apparently under the increased pressure, due to heating, the fingers would be bent away from the core, thus releasing the tooth laminations. Repeated tightening of the brass fingers did not relieve this condition. However, when the end plates were released ¼ in. at each end of the core, the brass fingers were then sprung in against the teeth and afterwards remained in position so that no breakage of tooth laminations was ever reported afterwards.

Obviously, with losses dependent upon pressure, no extreme accuracy in calculation of such losses is possible. However, in moderately small size machines, and especially in those of very moderate frequency and of very low voltage per unit length of core, the effect of pressure is not serious, within a moderate range of practicable pressures.

(e) Another source of iron loss, but which is not in the armature core, is that of the pole face, due to the tufting or bunching of the flux between the field pole and the armature teeth, where slotted armatures are used. Obviously, with all other conditions the same, this pole face loss will depend upon a number of variables in the lamination of the material itself. The effect of burrs from punching, the burring over of the surface due to turning, the effect of pressure, etc., all appear in the pole face loss. Therefore, it is evident that great accuracy in the calculation of such loss is impossible, in commercial apparatus. There are other conditions that affect this pole face loss which will be considered later under this subject.

Armature Ring Loss. The true iron loss in the armature ring is dependent upon the total flux per pole, distribution of flux, rate of change of flux, etc. The problem is much complicated by the fact that the flux distribution in the ring usually is not uniform, that is, certain parts of the core have higher maximum densities than other parts. However, in ordinary practise the core densities used are relatively low, so that the losses can be approximated by averaging the inductions in certain parts. However, the rate of change of flux in the ring is dependent, to a certain extent, upon the flux distribution in the air gap and armature teeth, and this introduces some error, always in the direction of increased loss.

The distribution of flux in the armature ring is also dependent upon the effective length of the various flux paths. These latter will naturally depend upon various conditions, such as the number of poles, diameter of armature, flux distribution in the air gap and teeth, etc. Therefore, any method which does not take this distribution into account is necessarily only approximate. However, in practise there are so many other variables, as already described, in connection with manufacturing conditions, such as burring, filing, etc., that empirical rules have been developed, based upon numerous tests, which approximate the armature core loss in a standard type of machine about as accurately as any attempt toward exact calculation.

Armature Tooth Losses at No-Load. Apparently the flux densities in the armature teeth can be calculated with more accuracy than in the various parts of the core, for in the teeth the fluxes are limited to fairly definite paths. Therefore, exclusive of the losses due to manufacturing conditions, as already described, the tooth losses can be fairly accurately calculated, probably with much greater accuracy than many other losses, as will be described. The tooth losses may be considered further as follows:

The flux density in each individual armature tooth passes through a cycle, indicated by the shape of the field form. With the field form of the shape illustrated in Fig. 1, the tooth density will be a maximum at *A*, and this density will remain practically constant as the tooth moves toward *C* until the point *B* is reached. It will then decrease as the ordinate of the field form curve decreases and will reach zero value at *C*. The cycle of flux change is not sinusoidal, and therefore, the actual tooth iron loss should not agree with that represented by the usual iron loss curves based upon sinusoidal changes in induction. The difference, however, may be relatively small in the ordinary types of machines. The error may be taken care of by some suitable correcting factor, which, of course, will be only approximate for the average case.

The density in the armature teeth is involved in the iron loss. This density is not uniform over the entire depth of the tooth, with the usual parallel-side slots, for the section of the tooth tapers off. This difference of section, in small diameter machines, may be very considerable. However, a higher density at the base of the tooth, tending to give higher iron loss, is compensated for, to some extent, by the reduced volume of material. In consequence, the mean section at some point from one-half to two-thirds the way down the tooth may be taken and the mean density and volume of material, based upon this section, may be used for approximating the iron loss. The accuracy of this method will be dependent, to some extent, upon the actual density used. For instance, if both the minimum and maximum densities in the tooth are relatively low, then the loss calculated for the mid-point density, at the mid-point section, will be closer to the true loss than if the maximum density is excessively high.

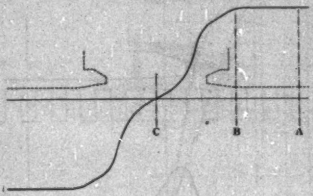

FIG. 1

Armature Copper Eddy Current Loss at No-Load. There may be a number of eddy current losses in the copper, some of which are of a minor nature. However, there may be two relatively large losses, depending upon the design of the machine. One of these is due to the flux from the field poles entering the armature slots and cutting the conductors. This is, to a certain extent, a function of the saturation of the tops of the armature teeth. It is also dependent upon the width of the slot opening compared with the iron-to-iron clearance. At first thought, one would say that the larger the air gap the more would the lines from the pole pass into the tooth top. However, the opposite is the case, for the larger the gap, the nearer do the lengths of paths into the slot approach to the iron-to-iron clearance, in percentage.

In moderate size machines with relatively small air gaps and moderate slot widths, the eddy current loss from fringing into the top of the slot is comparatively small, and, as a rule, no special precautions need be taken to minimize it. This particular loss is usually greatest in high-voltage, large-capacity turbo-alternators, where relatively wide slots, up to 1.5 in. or more, may be used, and where the air gaps are very large. In such cases lamination of the top conductors to avoid eddies from this cause may be desirable.

The second source of eddy current loss in the copper, which is liable to be larger than all others combined, is due to the peculiarities of flux distribution in the armature teeth. Let Fig. 2 represent the magnetic conditions in a given machine. It is evident from this figure that under the central flat part of the field form, the armature teeth are worked at a uniform induction, assuming that there is no field distortion. However, at the edges of the pole the tooth density decreases slightly. If the saturation of the teeth under the flat part of the field form is very high (materially above 120,000 lines per sq. in.), the ampere-turns required to magnetize the teeth may be very considerable. However, at the edge of the pole a comparatively small decrease in the flux density in the teeth (15 to 20 per cent) will mean a relatively enormous decrease in the ampere-turns for the teeth. For instance, the tooth *c* in Fig. 2, under the central flat part of the field form, may require 2000 ampere-turns, while the next tooth *b*, under the pole edge, which is worked at possibly 20 per cent lower density, may require only 10 to 20 per cent as many ampere-turns. Assuming such conditions, then the magnetic potential at the top of tooth *c* will be higher than that at the top of *b* by 1600 to 1800 ampere-turns. Therefore, under this condition there will be a very considerable flux across the slot between *c* and *b*. A little earlier or a little later in the rotation this flux across this slot will not exist to any extent, for the ampere-turns for *b* and *c* will then both be comparatively low or very high, while the difference between them will be small. In consequence, near each pole edge, there is a very rapid rise and fall of flux across the armature slots. This is illustrated in Fig. 2.

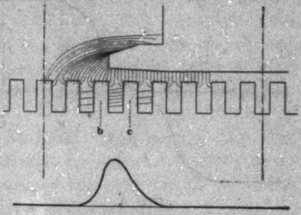

FIG. 2

Obviously, the armature conductors lying in the path of this flux will be the seat of e.m.fs. which will tend to set up local currents, the value of which will be some function of the e.m.f. producing the current, of the dimensions of the conductor, etc. If the flux across the slot is large, this e.m.f. may also be considerable, for the rate of this flux change will be high compared with the normal frequency of the machine. As the e.m.f. generated is a function of the maximum difference between the ampere-turns required for two adjacent teeth and as the loss in any given case will vary as the square of the e.m.f., obviously the loss in one slot will vary as the square of the maximum difference between the ampere-turns of two adjacent teeth. At very high saturation, the maximum difference between the ampere-turns required for two adjacent teeth may be relatively high and the loss may be correspondingly great. Due to the shape of the permeability curve of steel at very high saturation, the difference between the ampere-turns of two adjacent teeth may increase faster than the square of the terminal e.m.f. Therefore, the eddy current loss due to this cause may increase faster than the *fourth power of the total induction per pole.* Evidently, therefore, it is desirable to keep these eddy current losses at a low value at no-load, for the high tooth ampere-turns under the distorted field conditions of full load will tend to increase the percentage of these losses very greatly. Fig. 3 shows a characteristic core loss

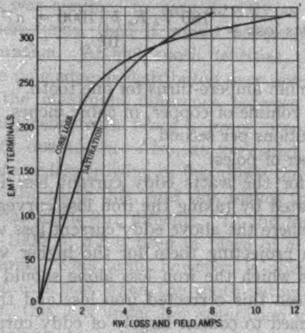

FIG. 3

curve for a generator in which the copper loss, due to the above cause, is very large at the higher e.m.fs.

Several years ago, the writer spent considerable time in attempting to determine the value of this eddy current loss at no-load. Neither sufficient nor entirely satisfactory data were available. From the data at hand, the following empirical formula was derived, which appeared to accord fairly well with the facts in a number of cases which were worked out. This formula applies, however, only to windings with two conductors in depth per slot. This formula for the loss in conductors is

$$\text{Watts loss} = \frac{180\ V_c\ R_s\ p\ (1000 + a)^2}{10^8}$$

a = Maximum ampere-turns for one tooth.
V_c = Total volume of copper, in cubic inches, in one slot.
R_s = Revolutions per second.
p = Number of poles.

The values for the watts eddy current loss in the copper were approximated by taking the iron loss curves at the lower e.m.f. values (where the above eddy current loss would be very low), and then projecting them for the higher values according to the laws which the iron loss alone should follow. The difference between this corrected iron loss and the actual test curve was assumed to consist largely of eddy current loss. As this difference usually increased very rapidly at higher inductions, the above assumption was in line with the preceding statements that this eddy current loss may increase much more rapidly than the square of the flux. In this determination obviously the pole face loss would have to be taken into account. This was taken care of as far as possible, by tests with relatively large air gaps, the pole face loss thus being very small.

It may be noted that in the above empirical formula, the ampere-turns for one tooth under the maximum field has been used, instead of the maximum difference between the ampere-turns of two adjacent teeth. However, the tests indicated in general that the maximum difference was approximately proportional to the maximum ampere-turns in one tooth and, therefore, it was simpler to use the total turns for one tooth. Also, where the total tooth ampere-turns are tapered off over several teeth, the difference between the ampere-turns for adjacent teeth is reduced, but more slots and more copper is involved, whereas the empirical formula includes only the copper for one slot. Various attempts were made to include all the different factors, such as ampere-turns across each slot, number of slots, number of conductors involved, counter magnetomotive force of the eddy currents, etc., but none of the resulting formulas gave as consistent results as the above. It must be admitted that this formula is an extremely crude one, but it happened to fit most of the cases that the writer was able to analyze. In deriving this equation, it was found that if the loss was assumed to vary directly as the square of the tooth ampere-turns, then it would be too great at very high tooth saturation. At high tooth densities, the flux across the slots, at the pole edge, is distributed over several successive slots, so that the maximum difference between the ampere-turns of two adjacent teeth bears a lower proportion to the ampere-turns for one tooth. Also, at very high tooth densities there is more or less fringing of flux down through the slot, in parallel with the tooth flux, and this makes the determination of the actual tooth flux difficult. In the formula, therefore, the term $(1000 + a)^2$ is used in place of a^2 to take care of these conditions. This term, however, is obviously wrong, in that it indicates a loss when the tooth saturation is negligible. However, this loss under low saturation usually works out from the formula to be of comparatively small value, so that the error is not of much importance.

A modified formula, which agrees with the above fairly closely at high saturations, but gives no loss at zero saturation, is the following:

$$\text{Watts loss} = \frac{135\ V_c\ R_s\ p\ (4000 + a)a}{10^8}$$

The following table shows the comparison of the copper eddy loss compared with the calculated loss by the first formula above, for a number of machines. It will be noted that the agreement is not particularly close, but possibly as good as could be expected, considering how the test losses were derived. It may be stated that these were all comparatively old types of machines, for in recent years great pains have been taken to eliminate large eddy losses of this character, so that it was necessary to go to old machines in order to obtain exaggerated cases.

Kilowatt rating	Terminal e.m.f.	Rev. per min.	No. of poles	Calculated ampere-turns in teeth	Eddy loss estimated from test curve; kw.	Eddy loss calculated from formula; kw.
340	600	685	6	1400	2.7	3.4
"	700	"		3000	10.0	9.7
500	600	225	10	2500	7.5	6.15
"	625	"		4000	17.5	12.5
750	250	514	10	1200	1.5	2.76
"	320	"		7200	32.0	39.3
750	550	514	8	1500	4.5	3.3
"	700	"		7000	33.0	36.5
1000	250	514	12	600	2.5	2.2
"	330	"		6000	50.0	41.3
1000	600	514	10	1225	4.5	4.6
"	700	"		2380	10.0	11.3
2000	575	300	14	3000	12.0	7.1
"	675	"		7000	36.0	28.2

Pole Face Losses at No-Load. It has long been known that, with open slot armatures, there are liable to be considerable losses in the field pole faces due to bunching of the magnetic flux from the armature teeth to the pole face, the armature teeth thus acting as small poles of an "inductor" type alternator, of which the pole face, to a small depth, serves the function of the armature core.

While the effect of this "inductor pole" action has long been known, the amount of loss due to it has frequently been underestimated, especially in machines with relatively small air gaps compared with the width of the armature slots.

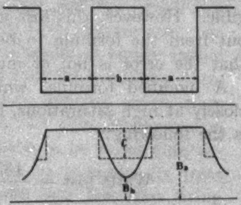

FIG. 4

The following crude description will illustrate the extent of the variations in flux in the air gap due to the open armature slots. In Fig. 4, *a* represents the width of one armature tooth and *b* represents the width of one armature slot. Let *g* represent the single air gap (iron to iron).

In the lower diagram, which represents the flux distribution in the air gap, let B_a represent the flux density in the air gap under the armature teeth and B_b the minimum flux density corresponding to the center of the slot.

Then, $a \times B_a$ = the total flux under one tooth, for unit width of core, and $b\,(B_a - B_b)\,c$ = the total decrease in flux for the space covered by one slot. c represents the average height of the curve *def* in Fig. 4. If this curve be assumed to be sine shaped, then c would be 0.636. Any other shape which would be likely to be found in practise would not be far from this value. A V-shape, as one extreme, would give $c = 0.5$, while a circular shape, as the other extreme, would give $c = 0.784$. Apparently the value would lie somewhere between these two extremes.

In calculating the effective gap from the above diagram and assumptions, the following equation would be obtained:

$$\text{Increased gap } g' = g \times \frac{(a+b)\,B_a}{(a+b)\,B_a - b\,(B_a - B_b)c}$$

$$\text{Or, } g' = g \times \frac{1}{1 - \dfrac{b\,(B_a - B_b)\,c}{(a+b)\,B_a}} = g \times \frac{1}{1 - \dfrac{(b)\,(B_a - B_b)\,c}{(a+b)\,(B_a)}}$$

The resemblance of this equation to Carter's well-known equation for the increased air gap may be seen at once.

$$\text{In Carter's equation, } g' = g \times \frac{1}{1 - \dfrac{b\,k}{a+b}}$$

Comparing these two formulas, it is evident that $k =$

$$\frac{(B_a - B_b)\,c}{B_a}.$$

An extremely close approximation to k can be obtained from the empirical formula $k = \dfrac{\dfrac{b}{g}}{5 + \dfrac{b}{g}}$. This holds closely to Carter's curve over almost the entire range. Equating the above two values of k, we obtain the equation

$$\frac{B_a - B_b}{B_a} = \frac{1}{c} \frac{(b)}{(5\,g + b)}$$

Or;

$$\frac{B_b}{B_a} = 1 - \frac{1}{c} \frac{(b)}{(5\,g + b)}$$

This gives the ratio of the flux density at the middle of the slot to the flux density under the tooth.

As an example of what these relative values may be, assume that $a = b$, or the slot width = the tooth width, and that $g = 0.25\,b$, which is extreme for large a-c. or d-c. generators, but not unusual for induction motors. Assuming $c = 0.635$, then $\frac{B_b}{B_a} = 0.3$, or the density under the middle of the slot is only 0.3 of that under the tooth. With these same values, the value of g' becomes 1.2859, or the gap increase is 28.5 per cent, which is not unusual for some machinery. Obviously, a variation in the flux density at the pole face of 70 per cent should tend to give high iron losses in the pole face itself. In fact, some of the inductor type alternators which were in common use a few years ago did not give variations in armature flux materially better than indicated by the above value. Such proportions as the above example would, therefore, be fairly good for an inductor alternator.

The above analysis is given simply to furnish a means for determining the possible variations in the flux density which may be obtained with open slots. This gives a much better conception of the problem than can usually be obtained directly from Carter's formula for the increased length of gap. It also gives a good idea of the possibilities of tooth losses in those cases where the teeth of one element or member of a machine alternately pass under the teeth and slots of the other member.

Considerable work has been done at various times to determine the pole face losses due to open armature slots. The difficulty in determining a workable formula is very considerable, as there are many conditions which may directly or indirectly affect this loss. For example, the thickness of the laminations, or the material in the pole face, may have an influence. Any general formula for this loss would require different constants for different types of pole faces. One formula for this loss has been given by Professor C. A. Adams and his associates.* The formula is very complex and somewhat difficult to use.

A much simpler formula for laminated pole faces is as follows, for 0.031-in. laminations:

$$\text{Watts loss} = \frac{75\, b\, E^2}{C_f\, W_s^2\, g\, L} \sqrt{\frac{S_c}{R_s\, g}}$$

E = Generator voltage.
b = Width of slot.
g = Single air gap (iron to iron).
W_s = Armature wires in series.
L = Width of pole face.
C_f = Field form constant.
S_c = Total slot space = width of slot × No. of slots.

It is very difficult to obtain any reliable data on pole face losses alone, for other core losses are liable to be included in any tests. Variation of air gap, with everything else in the construction unchanged, gives a partial measure. However, this changes the field form somewhat and thus modifies the

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**Pole Face Losses*, by Comfort A. Adams, A. C. Lanier, C. C. Pope and C. O. Schooley. TRANS. A. I. E. E., Vol. XXVIII, Part II, 1909, page 1151.

$$W_p = S_p \times p \times 0.000462 \left(\frac{B_g}{10^4}\right)^{2.4} \times \left(\frac{v}{10}\right)^{1.55} \times q^{1.5} \times \frac{1}{t_p}$$

W_p = Pole face loss.
S_p = Section of one pole face (average section where the density is B_g).
p = Number of poles.
0.000462 = Constant for $\frac{1}{16}$-in. laminations.
B_g = Density in the gap over the section S_p.
v = Velocity of the armature surface in feet per second.
q = Ratio of width of slot to air gap.
t_p = Tooth pitch in inches.

tooth saturation and the tooth and eddy losses, to a certain extent, thus rendering doubtful the pole face component.

The above formula is necessarily approximate and applies only to laminated pole faces. The effect of cutting away part of the laminations in order to produce high saturation at the pole face is not included. However, it is possible that this may not influence the loss to any great extent. The greater part of the loss is represented by eddy currents, and cutting away part of the laminations will tend to break up the losses between plates and this may compensate to a considerable extent for the higher densities in the remaining plates. It is hoped that some time in the future more complete data may be obtained, over a sufficiently wide range of conditions, to cover the practical range of ordinary design.

The following table covers a number of machines with adjustable air gaps in which the pole face losses were worked out according to the above formula. Also, the total calculated and the total test losses are given, to indicate the agreement in a general way. The writer is perfectly willing to admit that he believes that the fairly close agreements between some of the calculated and test totals are largely accidental, and they should not be taken as proof of any great accuracy of the methods.

It is obvious from this table that the pole face losses may be comparatively high in some cases, provided the formula is reasonably correct. Evidently, if these losses could be calculated with any great accuracy, the design of the machine might be considerably modified, compared with more recent practise, with advantageous results. The pole face losses will evidently be greatly increased by field distortion when the machine is carrying load. Eddy currents in the copper are also affected by field distortion, and a correct method of calculating both the eddy current and the pole face losses with various loads should lead to considerable modification in the proportions of d-c. machines, in general.

Stray Losses. Under this heading may be included a number of no-load losses which are usually of a minor nature. Among these may be included secondary losses in the armature winding due to unsymmetrical cross-connections or unbalanced voltages in parts of the winding which are connected in parallel. There are various possibilities for losses from this source and, in consequence, it is always advisable to use armature wind-

Kw.	E.m.f.	Rev. per min.	No. of poles	Single air gap; inch	No. of slots	Width of slots; inch	Tooth ampere-turns	Pole face watts	Calculated core losses				Total test losses watts
									Copper watts	Core watts	Teeth watts	Total watts	
200	250	1150	6	0.156	64	0.406	1635	2060	3660	1200	2500	9420	8500
				0.125			1887	2870	4400	1200	3000	11470	11600
200	250	1200	6	0.25	72	0.391	275	975	895	670	1450	3990	3800
				0.125			395	2200	1075	670	1650	5595	7300
750	250	514	10	0.25	200	0.312	2520	2530	7010	2560	5100	17200	19800
				0.1875			2820	3860	7410	2560	5320	19150	22000
750	550	514	8	0.375	200	0.328	2650	1190	7375	1945	3780	14290	14000
				0.250			2840	2210	7770	1945	4000	15925	15550
1000	600	514	10	0.281	140	0.625	2050	6380	15060	5290	6200	32930	30800
	700			0.281			3750	8680	36500	8320	7800	61300	62500

ings which are as symmetrical as possible. Also, the arrangement of the winding should be such as always to generate balanced e.m.fs. in parallel circuits. This condition is not infrequently overlooked in the design of direct-current machines.

A second cause of undue loss in the armature winding may be occasioned by short-circuiting one or more of the armature coils under an active field. The brushes may be shifted from the magnetic neutral point so that some of the armature conductors are short-circuited under the main field flux; or the neutral point may be so narrow and the brush so wide that some of the armature turns are short-circuiting in an active field, even when the brush is set for the no-load neutral. An armature winding which is considerably "chorded" in a field with a narrow neutral point may have two sides of a coil short-circuited in fields of the same polarity. The e.m.fs. in the two sides of the coil should, therefore, balance each other if the brush is set at the true neutral. However, if the brush short-circuits several coils or turns, obviously only one of them can be at the true neutral and have balanced e.m.fs. set up in its two halves. The other turns may have more or less local current in them, which may be a source of considerable loss.

A third condition may occur when there are considerable pulsations in the reluctance in the air gap under the main poles as the armature teeth move under the poles. This varying reluctance usually gives varying main flux and at a relatively high frequency. The armature coils short-circuited by the brushes will act as secondaries to these pulsating fluxes and in consequence there may be some loss in the short-circuited coils due to this cause. Any solid parts of the yoke or poles may also have losses due to this cause. Usually, however, such losses are small.

A fourth source of loss may rise from stray fluxes from the main fields to the armature, which do not pass through well laminated parts of the armature core. For instance, the ventilating spacers may be so dimensioned and shaped that eddies can be set up in them. Also, the finger plates at each end of the core, the end plates, etc., may carry light fluxes which produce some loss. Bands on the armature core or at the ends may also be the seat of e.m.fs. and will have some loss in them. These losses are difficult to determine, and, in practise, should be eliminated as far as possible.

FULL LOAD LOSSES

It is evident from the foregoing that the no-load core losses are dependent upon so many variable conditions that there can be no great accuracy in predetermining such losses unless all the details of construction, material, treatment, etc., are known for each individual machine. The impossibility of accurate calculation is shown by the fact that the individual machines built on the same stock order will vary considerably from each other, especially in certain types.

While the no-load losses are difficult to predetermine, the full-load losses are still much more difficult to calculate, as will be shown in the following rough analysis. Here, the effects of flux distortion by the armature magnetomotive force tend to exaggerate the pole face losses and those in the armature copper, which are the two relatively large losses which are most difficult to calculate at no-load. Also commutation and brush losses, due to load, now enter into the problem. The individual core losses may be considered briefly as follows:

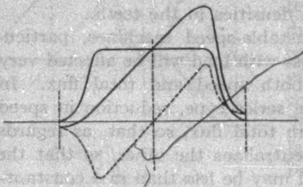

FIG. 5

Armature Ring Loss, with Load. This loss should not change greatly with load, provided the total flux at load is practically the same as at no-load. Under this condition a variation in the distribution of this flux is about the only factor which should produce any material change in loss. The full-load field form may be illustrated by Fig. 5. It is evident from this figure that the flux is now crowded toward one pole edge and, therefore, the major part is concentrated in a narrower space. The average length of the flux path may, therefore, be somewhat greater than at no-load, but in some cases this may tend to distribute the flux more uniformly through the depth of the ring. However, where the flux enters the core at the base of the teeth there will be slightly more crowding and, therefore, somewhat increased loss. Taking everything into consideration it would appear that, in general, the armature ring loss can be considered as practically constant with constant total flux and speed, independent of the variation in load.

In variable-speed and adjustable-speed d-c. machines, the armature ring loss may vary over a wide range due to changes in total flux and speed. Such cases are difficult to calculate with any degree of accuracy, although no more so than other losses in the same machines.

Armature Tooth Loss, with Load. As shown by Fig. 5, the tooth flux density at one edge of the pole is decreased and at the other edge is increased when the field flux is distorted by the armature magnetomotive force. The increased density in the armature teeth means increased iron loss and, if the distortion is very great, the increase in tooth loss may be very large, being in some cases even doubled or trebled, compared with the no-load tooth loss. No direct rule can be given for the calculation of this loss, except that it may be determined approximately by calculating the flux distribution with load and thus determining the flux densities in the teeth.

In variable-speed and adjustable-speed machines, particularly in the latter, the tooth loss with load will be affected very considerably by changes in both speed and total flux. In variable-speed machines of the series type, reduction in speed usually accompanies increase in total flux, so that, as regards the losses, one effect partly neutralizes the other, so that the increase in tooth loss with load may be less than in a constant-speed machine. In adjustable-speed machines, however, especially in those of constant horse power and constant voltage, the tooth losses will vary over a very wide range with change in speed. Here, the armature magnetomotive force is constant (assuming a constant horse power) and the field flux is varied from a maximum value at lowest speed to one-quarter value at four times speed, assuming a four-to-one range. The total flux, therefore, varies inversely as the speed and the two effects should nearly compensate each other, as regards losses, if it were not for the variation in flux distortion. At lowest speed, with considerable saturation in the pole horns and armature teeth, the armature magnetomotive force, even if relatively large compared with the field magnetomotive force, may not produce very large distortion, so that the tooth loss is not increased excessively over the no-load tooth loss. However, as the field is weakened, the armature magnetomotive force remaining constant, the distortion is relatively increased, so that the peak value of the distorted field may remain almost constant in height. As the armature tooth losses are dependent upon the peak value of this field, then obviously the combined effect of this field and the increase in speed will mean very greatly increased tooth losses. With very low field magnetomotive force, the distortion may be so great as to give a double peak, as indicated in Fig. 6. This double peak gives, to some extent, the effect of a double frequency and thus further increases the loss.

Eddy Currents in Copper. When the field form is distorted, with load, the ampere-turns in the teeth at one pole corner are greatly increased, while those at the other corner are decreased. Therefore, there will be an increased loss in the copper at one pole edge and a decreased loss at the other pole edge. However, as this loss at high inductions will vary almost as the square of the ampere-turns in the armature teeth, it is evident that the reduction in the loss at one pole corner may be small compared with the increase in loss in the copper at the other pole corner. The resultant loss can be calculated approximately by using the formula already given for no-load conditions, but with the ampere-turns in the teeth based on the load conditions. This would give a loss corresponding to no-load with the maximum induction in the teeth raised to peak value with load. This would include losses for the two pole corners; therefore, the result should be halved, as the peak density occurs at only one pole edge.

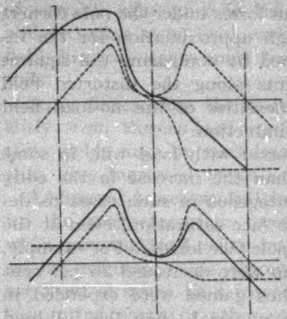

FIG. 6

If the empirical formula given for the copper loss represents the facts, even to a roughly approximate degree, the results are very startling when applied to some of the old-time machines. The calculations show that in some cases the eddy current copper loss at heavy load was several times greater than at no-load. This should be true, but to a much less extent, in more modern types of machines. The results indicate that in many cases there would be considerable gain by reducing the field distortion through high saturation in the pole face, pole horns, etc. This saturation, however, would have to be so arranged as to give the most beneficial field distribution with load, and haphazard methods of cutting off pole corners, without regard to the field form with load, would have to be avoided. In fact, in the past, the cutting away of pole corner laminations, in many cases, has been largely for the purpose of improving commutation, and not to obtain the best field form with load.

Pole Face Losses, with Load. The pole face losses will obviously be affected locally by change in the flux density in the air gap or at the pole face. Field distortion will tend to increase the loss at one pole corner and decrease it at the other. The increase will usually considerably exceed the decrease, but the resultant will not be increased in anything like the same proportions as the copper eddy current losses under the pole corners are increased with load. A rough approximation for the increased iron loss could be obtained by comparing the squares of the densities, at several points along the distorted field form, with the squares of the densities of the no-load field form corresponding to the total induction.

As the increase in pole face losses with load will, in some instances, be considerably less than the increase in the eddy current losses, it might be advantageous in such cases to decrease the field distortion by pole face saturation, even at the expense of increasing the no-load pole face losses. For example, if, in an extreme case, the air gap were decreased 20 per cent and the air gap ampere-turns thus gained were expended in suitably saturating the pole face material, then the full-load field distortion might be much less than with the larger gap, with the same total field magnetomotive force. The no-load eddy current copper losses would be practically unchanged, while the no-load pole face loss would be increased. However, the full-load pole face loss, due to the reduced distortion, might be no greater than with the larger gap, while the eddy current losses in the copper might be very much less than with the larger gap. In consequence, while the total no-load losses would be increased somewhat, the full-load loss would be smaller than before, and the carrying capacity of the machine would be actually increased. This would apply, however, only to those machines where the no-load eddy current and armature tooth losses are relatively high and where the distortion is rather large with load.

Stray Losses. When the machine is carrying load, the stray losses given under the no-load conditions may also exist and at the same time some of these may be greatly exaggerated. Also, other losses may appear which are not found at no-load.

Copper loss due to short-circuiting the armature coils in an active field will sometimes be more pronounced than at no-load, particularly in non-commutating pole machines in which the brushes are shifted into an active field to produce commutation. This field, as a rule, will only be of proper value to produce proper commutation at some definite load, while at other loads there may be very considerable local currents in the short-circuited coils, which may produce loss.

As the main field flux is crowded toward one pole corner and the field form becomes more pointed in shape, the effect of variable reluctance in the air gap may become more pronounced than at no-load, and, therefore, pulsations of the main field flux may cause more loss in the short-circuited armature coils.

Stray fluxes from the main poles will be distributed differently from the no-load condition and the densities of these stray fields may be considerably higher at certain points and thus give increased losses.

Additional losses at full load may be due to fluxes set up by the magnetomotive force of the armature winding itself when carrying load. For instance, the armature winding will set up magnetic fields, through the end windings, which fields are fixed in space, in a rotating armature machine. Bands or supporting parts, or other solid metal, rotating with the end winding, may cut these stationary fields or fluxes, and thus losses may be set up which are a function of the load.

Another source of loss at load may be found in the operation of commutation itself. A magnetic field or flux is set up by the armature winding across the slots from one commutation zone to the next. At the point of commutation this flux is reversed in direction with respect to the armature conductors, and, therefore, there will be local currents set up in the armature copper itself, due to this action. This, however, should be more properly charged to commutation loss rather than to armature core loss.

The above covers the principal core losses in direct-current machines. It was the original intention to analyze the core losses in the various types of rotating machines, but it soon developed that the subject was too extensive for the scope of this paper, therefore it was limited to d-c. machines only. However, many of the conditions which hold for d-c. machines also apply, to a certain extent, to many other types. In addition there are losses in d-c. machines which are relatively large compared with those in other apparatus, due to the fact that the tooth saturation in d-c. machines is frequently carried much higher than in other apparatus.

The foregoing treatment of core losses is qualitative rather than quantitative, and it deals with the simpler phenomena only. It omits some very complex conditions, such as the effect of pulsations in flux superposed on high densities, displaced minor hysteresis loops, etc., which mean additional losses. The principal object of the paper is to give a better idea of the possibilities and impossibilities of the problem of core losses.

DISCUSSION ON "IRON LOSSES IN DIRECT-CURRENT MACHINES" (LAMME), SCHENECTADY, N. Y., MARCH 7, 1916.

H. F. T. Erben: I agree with Mr. Lamme's statements that iron losses may be approximated with extreme accuracy but these approximations must be based upon past experiences. Mr. Lamme calls attention to the extremely distorted wave form often encountered in variable speed motors and instances Fig. 6 of the paper as being a typical case. While the field form as shown in Fig. 6 is a fair representation of the conditions that may be met in a three to one variable-speed motor, distortions of greater magnitude will be encountered if speed variations of four to one or five to one are attempted. I have in mind a four to one variable-speed motor which at no load and full load and maximum speed had field forms as shown in Fig. 1. It will be noted that at full load the field form was so distorted that there was an actual reversal of flux in the leading pole tip and the flux density at the trailing tip was fifty per cent greater than at no load. When one considers that the teeth in the trailing tip under these conditions are well up to saturation and that the armature teeth are subjected to double frequency, due to the reversal of flux, it is inevitable that there will be extremely high losses. Losses due to distortions of this nature can be obviated by either providing compensating windings or by using very large air gaps.

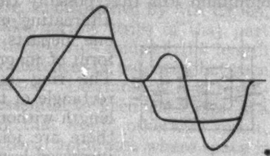

FIG. 1

Generators operating on the multiple-voltage system in connection with mine hoists and rolling mill equipments may have very high core losses under the condition of low voltage and maximum current. The high armature reaction gives rise to an extremely distorted wave form with high peaks. In order to counteract this condition, compensation is usually employed in generators of this type.

Mr. Lamme's paper has only touched upon losses in non-commutating pole machines. In commutating pole machines there is present a loss which is absent in non-commutating pole machines, namely the eddy current loss in the conductors directly under the commutating poles. The flux necessary to produce commutation may be of sufficient magnitude to cause appreciable eddy current losses in these conductors.

Generators and motors in which compensating windings are used are subject to core losses which are not inherent to machines of the commutating pole type. These losses arise through the variations in total flux, caused by the coincidence of the teeth in the armature and pole faces. Although extreme care may be exercised in arranging the relative position of the two sets of teeth it is almost an impossibility to get any combination of teeth which will not give rise to slight pulsations in flux. Any variation in the magnitude of the tooth flux will give rise to eddy current losses in both the armature conductors and in the conductors used in the compensated winding. I have cited these cases merely to show the extreme complexity of the problem which faces the designer in attempting to make a true estimate of the core losses of machines of modern type.

W. S. Moody: Transformers have no such percentage of losses to contend with as Mr. Lamme has shown us to exist in the case of generators and motors: yet the stray losses in a transformer are by no means negligible.

Most of the different kinds of stray losses which have been mentioned, exist to a minor extent in a well designed transformer and may easily be of a serious amount in a poor design.

If a given quality of sheet steel is made up into a ring shaped core, each lamination perfectly insulated from the others, the minimum loss that possibly can be obtained will result from alternating magnetization. Just as soon as one departs from this simple elementary form of magnetic circuit, the losses increase. The ring cannot even be made into a rectangle of the same cross section and mean length without an increase in the losses. If there are joints either interlocking or butt, increased losses come from the more or less cross flux that results. Again, cross flux gives stray losses when there is a different cross section in different parts of a transformer's core.

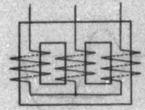

FIG. 2

A transformer core may have another kind of stray loss when the core carries multi-phase magnetization. In the common form of three-phase core as shown in Fig. 2, there is developed in parts of the core not covered by the windings multi-phase flux of a rotating character, which very greatly increases the losses in the iron in this part of the magnetic circuit.

The absence of air gaps and the fact that cores can be built without machining, are the principal reasons why the stray losses are less in transformers than in other apparatus.

Assuming the loss in a ring of laminations, which are perfectly insulated to be the minimum that can be obtained with a given grade of iron, transformers having a simple magnetic circuit can readily be built in which the stray losses are not more than 5 per cent, but when complex magnetic circuits are used and three-phase magnetization introduced, the stray losses in a transformer may readily run to 15 or 25 per cent of the normal losses.

Transformers also have stray losses in the copper, but unlike generators and motors, have stray copper loss only as the load comes on, as there is no flux in the wire space, except as result of the load currents.

Small transformers with small conductors have a negligible stray loss in the copper, but it is difficult in large transformers to keep the loss within a negligible amount, and in poorly worked out designs, the stray copper losses may readily reach such figures as have been mentioned for stray losses in generators.

Wm. B. Potter: The efficiency of electrical apparatus is certainly a subject worthy of most careful analysis. As Mr. Lamme has pointed out, there are often eddy losses of considerable moment other than those strictly chargeable to the magnetic circuit. The copper conductors, under conditions which are favorable to the generation of eddy currents, may in themselves have losses, which result in a temperature rise quite out of proportion to that from the useful current for which they have been provided. An extreme case I recall was a railway motor with armature conductors of unusual depth running in a field of high maximum intensity, and with the original solid bar winding the local current in these conductors was sufficient to cause a temperaature rise equal to that calculated for the energy current under full load. The remedy in this case, as mentioned by Mr. Erben, was to split the bars so as to make narrow strips of that part within the core, and criss-cross these strips midway the length of the slot so as to balance the differences of potential between the top and bottom of the conductor. Desirable as it is to improve the efficiency, it is often essential to keep the losses at a minimum because of the heating that would otherwise result, and this is especially true in electrical apparatus where space is of the utmost importance as is so often the case with railway motors. Probably more is required of a railway motor for its corresponding size and weight than any other electrical machine. The space is limited in width by the gauge, in height by the clearances between the vehicle and the track, in length by the wheel base, and it is fortunate that the maximum requirement has a limitation in the coefficient of adhesion between the driving wheels and the rail. The limitations of space for the railway motor are not only severe with respect to heating, but also the design is so compact, so surrounded by running gear, and operated under such adverse conditions that effective ventilation is a much greater problem than with stationary apparatus. A departure from the enclosed design of motor, depending on its external surface for radiation, to later types in which the armature is so designed as to act as a fan giving forced ventilation, has resulted in great reduction in weight and size for corresponding duty. In some classes of service where the conditions are not favorable to inherent ventilation, the use of external blowers as a supplementary feature has been found essential. It is most important that the losses should be eliminated so far as possible, and next of importance is to effectually deal with the losses that cannot be disposed of.

Friend H. Kierstead: Mr. Lamme in his reference to eddy current losses did not bother us with a statement of the peculiarities and erratic characteristics of these losses. I would like to touch upon the erratic characteristics of eddy current losses with reference to a transformer.

Let Fig. 3 be any conducting material being cut by magnetic flux. Then an eddy current will flow as is indicated in this figure. We can think of this conducting material as being the secondary of a transformer. Now, if its resistance be very high, it acts the same as the secondary of a transformer that is open circuited. If its resistance be very low, it acts the same as a short circuited secondary. The losses in the material due to the eddy currents will be affected by the flux density, by the frequency, by the shape of this conducting material and by its specific resistance. Eddy current losses are equal to $\frac{E^2R}{R^2 \times X}$ where E is eddy voltage, R is the resistance of the eddy circuit, and X is the reactance of the eddy circuit.

Now if the density of the flux that cuts the conducting material in Fig. 3 is changed, then, inasmuch as the only thing that is affected in the above formula by the density is the voltage, the eddy loss will increase with the square of the density, because the voltage is directly affected by the density.

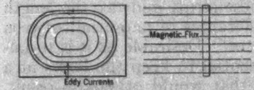

Fig. 3—Plan and End Elevation of Any Conducting Material Being Pierced by a Varying Magnetic Flux

Now, if the frequency be changed, then the corresponding change in the loss depends upon the relative values of X and R. If X be very small, as compared with R, the loss is equal to $\frac{E^2}{R}$ and an increase in frequency will increase the voltage, but will not affect the resistance. Therefore, when the reactance of the eddy circuit is small in comparison with its resistance, the eddy loss varies with the square of the frequency.

Take the other extreme, letting the resistance be very small as compared with the reactance, then the loss $= \frac{E^2R}{X^2}$ in which the eddy reactance and the eddy voltage vary with the frequencies, to the same extent. In this case, the eddy loss is not affected by the change in frequency.

An illustration of the former case is in the laminations in the iron of the transformer where the reactance of the eddy circuit is very low and the resistance is comparatively high. An illustration of the second case is in the short circuited transformer where the resistance of the winding is very low in comparison to the reactance, and in this case the losses in the winding do not change greatly with the frequency.

Let us consider now how these losses change with the dimensions of the conductor. Let the conducting material in Fig. 3 become greater in extent, in such way that the flux cutting it also increases. Then the eddy voltage increases as the conductor increases, and so also does the reactance to the same extent.

Now, if the reactance is small in comparison with the resistance the loss $= \frac{E^2}{R}$ and since the eddy voltage increases and the resistance decreases with increase in the cross-section of the conducting material, the eddy current losses increase greatly as the cross section of the conducting material increases.

Now, if R be small in comparison with X, the loss $= \frac{E^2 R}{X^2}$ and E and X are increasing together, and R is decreasing. Then the eddy losses are decreased by increasing that conductor.

The eddy losses are influenced by the specific resistance. If the specific resistance of a given conductor is changed without changing anything else, then neither the eddy voltage or the reactance is affected. Therefore, if the reactance be much greater than the resistance, the loss $= \frac{E^2 R}{X^2}$ and the eddy losses increase with increase in specific resistance directly, but if the resistance is great in comparison with the reactance, then the loss $= \frac{E^2}{R}$ which shows that eddy loss is decreased by increasing resistance.

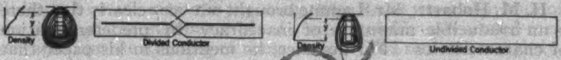

FIG. 4 FIG. 5

DIAGRAMS OF FLUX DENSITY

Departing from above analysis, and taking up the divided conductor in the slot-wound machine. Reference was made to a d-c. machine. Fig. 4 shows such a divided conductor in a slot.

In a d-c. machine where the eddy loss in a conductor is not created by the current which flows through it, but by flux which is independent to a great extent of the current in the conductor, this dividing reduces the loss, but in the case where the eddy current is produced by flux, which in turn is produced by current flowing through the conductor, dividing the conductor may not reduce the loss. Let the field produced by current flowing through the conductor be as indicated in Fig. 4. Now if the conductor were not divided, as is indicated in Fig. 5, then the greater portion of the current would flow in the top of the conductor and the average density of the flux cutting the conductor would be reduced. However, since the conductor is divided, the same amount of current has to go through the bottom as goes through the top. Therefore, inasmuch as half the current is forced to stay down near the bottom of the slot then the average density is greater than in the undivided conductor and the difference increases with frequency, and therefore the loss in the divided conductor may be greater than it would be if it were not divided, providing the frequency be high enough.

While working under the direction of Mr. H. M. Hobart, we had a problem to increase the loss in an induction motor at starting so as to get greater starting torque, and we actually made up test models to test the losses in the divided and undivided conductors, and we found when the frequency was low the undivided conductor gave greater loss, but when the frequency was high, the divided conductor gave greater loss. It depended upon the depth of this conductor and the frequency. As I remember, when we made the conductor three inches deep, and had 60 cycles flowing through it, the divided conductor gave greater loss.

H. M. Hobart: Mr. Lamme brought out very clearly that there is an irreducible minimum of inaccuracy in predetermination of characteristics. For instance, he mentions in his paper that two machines built on exactly the same specifications, with exactly the same tools, may vary in core loss by 20 per cent.

If Mr. Lamme's paper had not been confined to a discussion of iron losses, if he had touched on commutation, or on regulation, or on the predetermination of temperature rise, or on anything of that sort, the limits which he would have shown for the irreducible minimum of inexactness would probably have been expressed in larger figures than 20 per cent.

Mr. Lamme's assertion relating to 20 per cent inexactness was with respect to the no-load core losses, and he pointed out that it was not exclusively the iron loss, but that there were often also losses in the copper conductors which were included in that expression.

It is a fact that in the completed machine these no-load losses are almost always at least three or four times the loss (reduced to loss per ton) which would be obtained in a test made on a laboratory sample. Transformers constitute an exception; in their case there is no such large multiplier, but even there we do not get down to the losses measured on the test samples.

In machines where the greatest care is taken to keep these losses down, for instance, in induction motors, the multipliers are not so great as in other types.

Mr. Potter alluded to the difficulties concerning weight of, and space occupied by railway motors. I have plotted many curves from factory tests to obtain the factor by which to multiply the laboratory loss (the loss of the test sample), in order to obtain the loss in the actually completed machine, and that multiplier was larger in railway motors than it was in any other kind of machine. In induction motors the multiplier is reasonably low. In a-c. generators it is decidedly high. These statements relate to the no-load losses.

When we come to the load losses, the observed idiosyncrasies are, of course, all really based on physical laws; such as those to which allusion has been made in the paper; absolutely simple physical laws always being obeyed; but there are so many of these laws that we cannot keep track of them, and at load the losses are often much greater than we estimate. The simple old fashioned efficiency, in which we placed so much faith, is often distinctly higher than the efficiency realized in practise. It is simple enough to measure the efficiency to almost any degree of accuracy, if there is money enough available to spend on the test, but in commercial transactions you cannot arrange for tests that cost as much as, or much more than, the machine itself, and we have to resort to empirical allowances for the various obscure losses.

We are all familiar with the new Standardization Rules issued by the American Institute of Electrical Engineers; the American Rules. A prime mover in creating these Rules was the author of the paper of the evening. Mr. Lamme steadily advocated conservatism in the drafting of these Rules. If I remember rightly, the first suggestion of the plan underlying the "Conventional Efficiency" came from Mr. Lamme. He realized that we could rarely make these laboratory tests which would give the true efficiency, and the only reasonable commercial thing to do was to make sensible assumptions for some of these obscure losses, and he always said—"Let us make these allowances large, let us make them such, that as far as we can foresee, they are certain to at least, cover these actual losses," and so we have in the Rules certain allowances, and it has been the aim of the Standards Committee, that the so-called conventional efficiency, following the recommendations of the Rules, will generally be fully as low as the true efficiency at which you could arrive if you were to make the expensive tests which would be necessary.

Mr. Lamme referred to the subject of temperature rise and I believe it is allowable to make further allusion to the matter. The previous Rules were of some use in this respect; they would give us some rough notion of what the temperature of the parts of the machine might be. As the years advanced, we gradually accumulated convincing evidence that the so-called actual hottest spots in the machine were often far and away above the temperature you obtained with thermometers. Mr. Lamme's attitude was: "Let us recommend certain methods of getting at the very highest temperature, make a clean breast of it, let everybody know that these machines are running at such and such a high temperature." Consequently it was necessary to readjust the temperature limits, so as to make things square up.

That was a very good plan. It recognizes the high plane which should be occupied by engineering.

There is no use in figuring efficiencies higher than they really are. There is no use in employing ideal but unattainable curves in estimating core losses. Let us take a curve which will be sure not to leave us in the lurch. Do not let us employ the ideal curves and say—" This is the predetermined temperature rise in this machine," or " this is the predetermined efficiency of this machine," or whatever it may be, and then never realize such results.

I should like to call attention to a letter which very opportunely reached me today. I thought it was so relevant to this particular subject that I would refer to it. It is from a British engineer, Prof. Miles Walker. He alludes to the A. I. E. E. Standardization Rules, in paragraphs 452 and 453. These paragraphs define the no-load losses. The letter was so appropriate to the paper, and so thoroughly corroborates the general attitude that Mr. Lamme has emphasized, that I thought it would be interesting to refer to it. In reference to these paragraphs Prof. Miles. Walker says:

" Under the heading 'No-Load Core Losses,' of course this refers to all the losses usually included in an 'iron loss test,' and it would be well to have a statement in the Rules that these include all eddy current losses in armature conductors and frame which occur at no load. There is a good deal of evidence on some classes of machines that a *very large proportion* of the no-load losses are not core losses."

William J. Foster: Several years ago an alternator was built that was three or four times as large as anything previously attempted—it was a vertical shaft machine; the weight of the core was great, and the clamps were made much stronger than ever before. The machine was put together with great pressure, to say nothing about the weight of the core itself, which exerted great pressure on the lower part of it. When that machine was tested we were disappointed in the efficiency, as the guarantee had been high and the calculated efficiency was high. It occurred to some of us inasmuch as every element in the design was favorable to a very low iron loss such as narrow slots with respect to the air-gap and reasonable magnetic densities, it might be due to the fact that the core was not really laminated as we thought, and so the second core was put up with considerably less iron in it. This core was tested without putting the regular winding in, but simply a potential coil, so we knew when we had the normal magnetic densities. We found a decided improvement in the loss, something like thirty or forty per cent.

Then we started in to put in more and more iron, and got back to where we were in the first instance. In that particular case we came to the conclusion that we did not know how to insulate our laminations for that kind of work. We then started in to develop a better method of insulating.

Confining ourselves strictly to the iron losses, I am a great believer in the proper lamination of the poles where we build with open slots and have non-magnetic retaining wedges. There, again, in my experience we have had just as great surprises in the old days as in the case of this core that was put together with too great pressure for the insulation that was used. There is always, in the case of revolving field alternators where it is necessary to look out for the safe mechanical structure, a temptation to use laminations in building up the poles that are too thick to give good results in the matter of the core losses. We have gotten in the way of using core loss constants with reference to the product of several factors, such as the thickness of the laminations, the tooth frequency, the breadth of the slot and length of the air-gap.

In speaking of iron losses, as confused with eddy current losses in the conductors themselves,—an interesting case, came under my observation in connection with a turbo-generator, of about 15,000 kw. which had a current something like 900 to 1,000 amperes, which we had to handle in a single circuit. The problem first came up in connection with a 25-cycle generator which was developed with a certain conductor, that proved to be an excellent machine in all respects, having high efficiency and low heating, the temperatures being determined by temperature coils embedded in the heart of the slot. By a little slip, or a little forgetfulness, you may say, the same conductor was put into a machine of practically the same capacity, but 60-cycles, where there were just three or four factors differing enough to make that second machine an impossible one as far as meeting the temperature guarantees were concerned. The conductor was laminated, with every strand insulated throughout the entire length. The winding consisted of two conductors per slot with connection clips at both ends, which solidified or short-circuited all the strands of the conductor. In the case of the 25-cycle machine, the core was relatively short and the pole pitch large. The length of the core represented the e. m. f. or one factor in determining how much current was circulating between the top and the bottom of that conductor, while the total length of conductor represented the resistance or the other factor. The current in one case was two or three times that in the other, and the eddy losses were several times, six or seven times as high in one machine as in the other per unit length of conductor. The consequence was in the first machine they amounted to a reasonable percentage of the legitimate I^2R loss, say 20 or 30 per cent, and in the other case they were so large as to raise the temperature to a dangerous point. A change had to be made in that 60-cycle machine. The 25-cycle machine is still operating,—a number of them,— with very conservative temperatures. That was simply an instance of oversight in designing.

Joseph L. Burnham: As Mr. Lamme has stated the "treatment of core losses is qualitative rather than quantitative and it deals with the simpler phenomena only," although these phenomena are of major importance. The value of the paper seems to me not to be so much in the methods of calculation developed as in calling attention to the conditions to be avoided. The calculations are rather complicated for practical work and depend too much upon known characteristics of the material (which cannot be depended on) and also upon experience which can only be obtained from the results of many tests.

The previous speakers have mentioned the advantages to be obtained from the use of compensating windings but have not mentioned that there are other sources of loss induced by these windings which are very similar to the losses caused by variations in flux density as described by Mr. Lamme and represented in his Fig. 2. By the multiplication of the compensating windings made necessary in modern machines of high armature reaction, the space in the pole face becomes crowded so that care must be taken that local densities are not high thus causing unequal flux distributions. Furthermore, the opposing magnetization of the compensating windings and the armature conductors tends to set up a flux around the periphery of the armature, so that, to avoid the bunching of this flux at the pole tips, the reluctance of this path should be made high. If the compensating conductors are not placed quite close to the surface of the pole face, there should be narrow slots in the pole face between the compensating conductors and the pole face parallel to the conductors to increase the reluctance around the periphery of the pole face.

L. T. Robinson: I will add one word to cover the point that Mr. Hobart brought out. I think there may be a little doubt in the minds of some of you as to the difficulties of making iron loss tests agree with the losses computed from determinations made on rings or other samples. I do not think there is any difficulty in arriving at an answer, which is as correct as you can arrive at anything where the material itself is subject to so much variation.

You cannot, certainly, predetermine the core losses closer than you can know the properties of the material which you are going to use, and you do not know that very closely. That must be assumed. In cases where it has been possible to know exactly what the material is, it has been possible to get very close. I am sure you could get similar results in other cases, if you knew where the flux went and how much of it went in certain places. As bearing on that point, I notice that certain figures for magnetic flux density have been referred to as 180,000 lines ($B = 28,000$). This estimate is much higher than I believe it should be. The assumption is no doubt made that whatever flux goes through the armature is bound to go through the teeth. Under the conditions of use the permeability of these teeth is very low, and no doubt a large percentage of the flux goes through the slots.

A. S. Langsdorf (by letter): The best determinations of pole face losses and of empirical formulas for their calculation have been made by operating a machine as a motor and subtracting from the input the sum of the other losses. It is well known that a method which involves the evaluation of a relatively small quantity by taking the difference between two relatively large quantities is liable to considerable percentage error even under the most favorable conditions; and in the case of such a determination of pole face loss the inaccuracy is still further enhanced by the fact that the sum of the " other losses " is difficult to determine because it includes such uncertain items as losses due to flux pulsation, brush contact, eddy currents in armature conductors, and distortion of flux caused by armature reaction.

Considerations of this kind led the writer to the conviction that a reliable determination of pole face loss could be made only by a radical departure from previous test methods and by the development of apparatus that would permit the direct measurement of the pole face loss itself. To this end there has been designed a special machine built along the lines of a homopolar generator, as indicated in Fig. 6. The frame consists of an annealed steel casting of *E* section with an exciting coil wound on the central core. In the annular space between the central core and the overhanging outer ring (the pole face) there is centered an unwound, laminated toothed core assembled on a cast iron spider carried by a shaft mounted in ball bearings. The toothed core is driven by an adjustable speed motor through a torsion dynamometer. The only losses that can occur in this machine are the pole face loss and the friction and windage loss; hysteresis is eliminated because of the fact that the core is traversed by a unidirectional, unvarying flux; eddy currents are eliminated provided the flux is uniformly distributed around the gap, a condition that is easy to obtain by accurate centering and which has been shown to exist by careful tests. Friction and windage at any speed can be entirely eliminated by taking as zero reading of the dynamometer that setting which corresponds to the condition of zero field excitation, hence the pole face loss can be read directly.

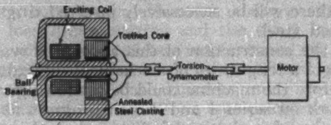

FIG. 6

The apparatus readily lends itself to the following series of tests:

1. *Dependence of the pole face loss upon average flux density in the air-gap.* In this test the speed of the core is kept constant and the field excitation is varied, the value of the gap induction being determined by the reading of a voltmeter connected through slip rings to a piece of insulated wire stretched across the tip of a tooth.

2. *Dependence of the pole face loss upon peripheral velocity of teeth.* In this test the flux density in the gap is kept constant at some convenient value.

3. *Dependence of the pole face loss upon the slot opening.* For this purpose two interchangeable cores have been provided, one having straight open slots, the other semi-closed slots.

4. *Dependence of the pole face loss upon length of air-gap.* After completing series 1, 2 and 3, the pole face is to be bored out slightly and a new series taken, this process being repeated until the air-gap has been increased to a point where the pole face loss is negligible.

5. *Dependence of pole face loss upon material and construction of pole face.* After the completion of the four series outlined above, the overhanging cast steel pole face will be cut away and in its place there will be successively inserted rings of cast iron, and laminated steel.

Although the construction of this apparatus was undertaken some time ago, a long series of mechanical difficulties had to be overcome before the machine could be made to give dependable results. Work on series 1 and 2 is in progress at this writing. The results thus far obtained indicate that the pole face loss varies at a slightly greater rate than the second power of the gap induction, and very nearly as the 3/2 power of the peripheral velocity, in accordance with theory. The writer hopes to be able to present detailed reports at a later date.

B. G. Lamme: Mr. Erben, in his discussion, has referred to certain pole shapes which reduce flux distortion with load and thus lessen or prevent iron losses due to increase in load. However, the arrangements which he has shown are not suitable for reversible operation, especially where there are liable to be very heavy loads with weak fields. For instance, take reversing mills working on the variable voltage system, where there are frequent excessively heavy currents at almost zero field fluxes. In such machines, as a rule, compensating windings are used to prevent flux distortion, primarily to avoid high voltages between commutator bars and to help commutation. Reduction in armature core loss is not a first consideration in such machines, but the compensating winding, of course, does reduce the loss somewhat.

Referring next to the point which Mr. Hobart mentioned, namely, the desirability of admitting that we cannot calculate certain things in electrical apparatus, with any great accuracy; I have always been a believer in the doctrine that if there are limitations to our doing a certain thing, it is much better to recognize such limitations and admit them, and in that way more progress will be made. If we cannot calculate all the losses in a machine with any great accuracy, it is better to analyze them, as far as possible, and find where and why accuracy is not practicable. We should recognize what we cannot do and what the real limitations are and we are then in a much safer position than if we go ahead blindly. For many years the Standardization Rules of the American Institute of Electrical Engineers were very apt to mislead the public. For instance, in the problems of temperature measurements, practically everybody outside of the manufacturing companies thought that accurate temperature determination was a practical condition. One of the great things we did in the last revision of these Standardization Rules, was to show the possibilities of inaccuracy in temperature determination. We openly admitted that temperature measurements as carried out practically, were only approximations, and, in my opinion, in taking this stand we really took a long step forward in the art. The same holds true in regard to efficiency. If we know that we cannot measure it exactly and will tell why we cannot do so, then by so much we advance the art. The same holds true with core losses. However, there is this difference between core loss determination and the other instances just cited, namely, core losses can be predetermined with very considerable accuracy, by what may be considered as empirical methods. These calculations, however, may be considered more in the nature of estimates than true calculations.

The point which I wish to bring out in particular is, that if we know wherein inaccuracies are liable to occur in our calculations, and also know how much the errors are liable to be, in new classes of work in particular, then we are in a position to allow sufficient margin of safety. The difference between experience and inexperience in a designer, is often indicated by this margin of safety.

Presented at the 319th meeting of the American Institute of Electrical Engineers, New York, March 10, 1916.

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THE INFLUENCE OF FREQUENCY OF ALTERNATING OR INFREQUENTLY REVERSED CURRENT ON ELECTROLYTIC CORROSION

BY BURTON MCCOLLUM AND G. H. AHLBORN

ABSTRACT OF PAPER

This paper describes experimental work done to determine the co-efficient of corrosion of iron and lead in soil with varying frequencies of alternating or reversed current with 60 cycles per second as the highest frequency and a two-week period as lowest—some d-c. tests being made as a check on the methods. The results show (1), that a decrease of corrosion occurs with an increase in frequency; (2), that the corrosion is practically negligible below a five-minute period; (3), that there is, a limiting frequency above which practically no corrosion occurs; (4), that certain chemicals affect the natural and electrolytic corrosion of the two metals quite differently; (5), that the loss of lead in soil on direct current is about 25 per cent of the theoretical loss; and (6), that alternating or reversed current with as long periods as a day or a week would in the case of iron materially reduce the damage to underground structures.

The importance of these results grows out of the fact that there are large areas in practically every city in which the polarity of the underground pipes reverses with periods ranging from a few seconds to an hour or more due to the shifting of railway loads. The investigation shows that the corrosion under such conditions is much less than has generally been supposed.

I. INTRODUCTION

THE TERMS "electrolytic corrosion" and "electrolysis" have been used to designate corrosion caused by the discharge of electric currents which entered the metal from outside sources. In this paper the term a-c. electrolysis applies not only to electrolysis from ordinary alternating currents of commercial frequencies, but also to alternating currents of much longer periods, such as several minutes or even a day or longer. Alternating currents of such long periods are very common on portions of underground pipe systems of practically every city due to the continual shifting of railway loads which causes the pipes within a large area, commonly called the neutral zone, to continually change their polarity with respect to the earth. In this paper the term "coefficient of corrosion" is frequently used in connection with the corrosion of an anode. This factor is the ratio of the actual corrosion observed to that which would have occurred if all of the electrode reactions determined by Faraday's law had been involved solely in corroding the anode. Thus if the theoretical corrosion in any case was 100 grams and the observed corrosion 46 grams, the "coefficient of corrosion" would be 0.46. This is sometimes called "efficiency of corrosion."

IMPORTANCE AND SCOPE OF THE PRESENT INVESTIGATION

Since most of the electrolysis which occurs is due to stray currents from electric railways, and since only a small percentage of these operate with alternating current, it might seem at first thought that a-c. electrolysis is of rather infrequent occurrence, and that the problems connected with it do not deserve much attention. However, in addition to the railways which use alternating or reverse currents as motive power, such currents often result as an incident of railway operation. These occur not only in the ordinary negative systems of railways as mentioned above, as the trolley load shifts from point to point on the track with the movement of the cars, but they occur to a greater extent and in a much larger territory in the case of negative return systems in which insulated negative feeders are used. In such systems the potential differences between pipes and tracks can be greatly reduced, but this is accompanied by a large increase in the area of the so-called neutral zone in which the polarity of the pipes is continually changing from positive to negative. With certain types of three-wire systems which are now being seriously considered in some places for the prevention of electrolysis, there will be large areas in which the polarity of the pipes will fluctuate between small positive and negative values. It has also been proposed that with the usual type of return that the trolley be made alternately positive and negative on succeeding days or weeks. All of these methods would have the effect of reversing the current flow on underground structures, and the period of the cycle would vary from a few seconds to a day or longer. Moreover, the frequent grounding of 60-cycle lighting circuits permits a certain amount of leakage from those systems, and the corrosion produced, especially in case of accidental grounds on other parts of the system, would be of considerable importance if alternating current gave rise to serious corrosion. It is therefore of great practical importance to determine the extent to which periodically reversed currents of these long periods will produce corrosion on subsurface metallic structures.

WORK OF PREVIOUS INVESTIGATORS

A number of writers have advanced theories concerning laws governing a-c. electrolysis and a considerable amount of experimental work has been done with frequencies of 25 to 60 cycles. One writer, discussing the phenomenon from the standpoint of the decomposition of the electrolyte,[1] arrives at certain conclusions: (1), That the quantity of electrolyte decomposed by alternating current is less than by direct current; (2), that it is proportional to the electrode current density; (3), that there is a limiting electrode current density below which no decomposition of the electrolyte occurs; (4), that the quantity decreases with an increase in the frequency of alternations, and that there is a limiting rapidity of alternation above which there is no decomposition. Conclusions (1), (3), and (4) seem borne out by the experimental work described later.

With reference to the dynamic characteristics of electrolytic cells, several writers have determined by experimental work,[2] chiefly with the oscillograph, that such cells affect the wave form. As one writer states, the chemical polarization in the cell causes it to behave as a variable condenser with a resistance in parallel and in series.

With a very special set of conditions one experimenter[3] has noted an amount of corrosion of the electrodes varying from zero to 35 per cent, with 60-cycle current, and he arrives at the conclusion that the corrosion is practically independent of the current density of the electrodes and temperature; and also that stirring of the solution has no effect. He states that the corrosion does depend on the condition of the electrode surface but does not attempt to state the principle of this variation.

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[1] Dr. Guglielmo Mengarini, *Electrical World*, Vol. 18, No. 6, p. 96., Aug. 8, 1891.

[2] Ruchinstein, D. Electrolysis with Alternating Current Dynamic Characteristic of an Electrolytic Cell. *Zeitschrift für Electrochemie* December 1, 1909; LeBlanc, M. The e.m.fs. of Polarization and their Measurement by the Oscillograph. Deut. Bunsen Geselschaft. No. 3. Alternating Current Electrolysis Use of Oscillograph in Connection with Polarization. *Zeitschrift für Electrochemie* 11, 707, 1905.

[3] White, G. R., Alternating Current Electrolysis with Cadmium Electrodes.

Experiments of more practical importance to the engineering world were conducted in 1905.[4] Twenty-five-cycle current was impressed on iron and lead pipes buried in soil and it was found that the corrosion was practically the same as that due to the soil alone. No figures of exact losses are given. Alternating current of 25-cycle frequency was impressed on lead and iron plates in salt solution and direct current was impressed on other plates in a similar electrolyte and it was found that the loss was negligible for the alternating current and very large for the direct current.

Only a year or so later a large number of tests were conducted with 25-cycle, 60-cycle, and direct current on iron and lead plates.[5] The conditions were varied by using different soils, salts added to soils, varying the temperature and current density. The results show that although there is quite a large variation in the loss with different specimens and that the 25-cycle losses are uniformly greater than the 60-cycle; these losses never exceed one per cent under normal temperature conditions. The writer notes that some salts, for example, carbonates and alkaline compounds, reduce the electrolytic corrosion of lead plates. He found that an increase of temperature to 40 deg. cent. increases the corrosion to about one per cent. His final conclusions are that a-c. electrolysis is more irregular than d-c. electrolysis, that nitrates increase corrosion and carbonates generally decrease it, but that the effect is not great enough to be of practical use for protecting lead cables; that lead is more readily attacked than iron; that the current density does not appreciably affect corrosion except indirectly by increase of temperature; and that the corrosion increases with a decrease in frequency. He attempts to protect lead specimens by making them negative either by connecting them to a zinc plate or with a small direct current, and finds that the loss is considerably less than with the alternating current alone. He finds that a current of one per cent of the value of the alternating current is sufficient to give practically complete protection, the corrosion in some instances being less than that due to natural corrosion alone. It will be noted in the above experimental work that the different variables employed, such as current density, chemicals, temperature, etc., do change the action of alternating current, but that in practically no case did the losses exceed one per cent. When we consider the large variation of the electrochemical loss produced by direct current under identical conditions, it is evident that differences obtained between 25- and 60-cycle current are practically negligible.

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[4] Kintner, S. M., Alternating Current Electrolysis, *Electric Journal*, Vol. 2, p. 668, 1905.

[5] Hayden, J. L. R., Alternating Current Electrolysis, TRANS. A. I. E. E., Vol. XXVI, Part I, p. 201.

PURPOSE OF THIS PAPER

The data discussed in this paper were obtained as a part of the general investigation of electrolysis conducted by the Bureau of Standards. Its object is not to determine the laws which govern electrolytic corrosion at any one frequency, but to take a standard set of conditions approaching as nearly as possible those existing in practise, that is, wrought iron pipes and lead sheaths imbedded in soil and to determine the corrosion which will occur in the range of frequencies mentioned above, namely, for frequencies ranging from 60 cycles per second to a week or more per cycle. These data will be of material assistance in determining the effectiveness of many of the proposed systems of electrolysis mitigation.

II. DISCUSSION

PRELIMINARY EXPERIMENTS ON EFFECT OF CIRCULATION OF ELECTROLYTE

Before beginning the more complete series of tests to determine the effect of change in frequency, a number of preliminary experiments were carried out in order to throw light on certain theoretical aspects of the question under consideration. Theoretical considerations led to the belief that the corrosion of frequently reversed currents would be materially increased by rapid circulation of the electrolyte and diminished by conditions which tended to restrict such circulation. If this were true it was reasoned that in the case of metals buried in soils, in which the circulation of electrolyte is greatly restricted, relatively little corrosion would occur even with periodically reversed currents of long period. Accordingly, a number of experiments were carried out to determine the effect of circulation of the electrolyte on the coefficient of corrosion.

A set of four cells with wrought iron electrodes and a one per cent NaCl solution as the electrolyte were connected in series on 60-cycle current. The electrolyte in cell No. 1 (see

Fig. 1) was stirred by a small turbine and in No. 2 the electrolyte was undisturbed; in No. 3 the electrodes were wrapped with filter paper; and in No. 4 the electrolyte was prevented from mechanical circulation by gelatin. Iron electrodes which were carefully weighed were connected in the circuits and the current was maintained at about a half ampere for nearly 200 hours. At the end of the run the electrodes were again weighed and the loss determined by difference from the initial weight. Based on the theoretical loss, which would have been about 100 grams, the coefficients of corrosion (see Table I) are 0.0034 for the stirred electrolyte; 0.002 in the stationary solution; 0.0009 when protected by filter paper; 0.0007 in the gelatin. It seems evident that the chemical action is not as reversible when the electrolyte is in motion about the electrodes as when stationary. In order to determine this effect more exactly a single cell was con-

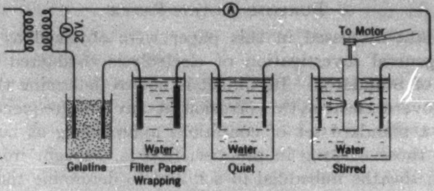
A
V
20V.
To Motor
Water
Water
Water
Gelatine
Filter Paper Wrapping
Quiet
Stirred

FIG. 1—ARRANGEMENT OF FOUR CELLS

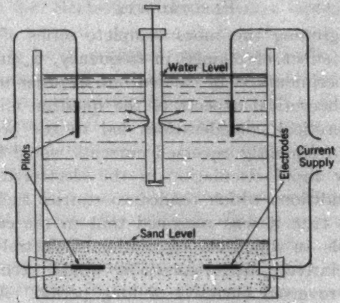
Water Level
Pilots
Electrodes
Current Supply
Sand Level

FIG. 2

nected as shown in Fig. 2. Here there were two electrodes with no current impressed to determine the natural corrosion and two serving as current electrodes. One of these was in the electrolyte stirred by the turbine and the other was wrapped in filter paper and buried in sand saturated with the solution. After correcting for the natural corrosion it was found that the coefficient of corrosion was 0.0004 for the upper electrode and 0.0001 for the lower. The results are shown in Table I. The same type of cell was operated on 20-cycle alternating current with the losses as shown in Table II. It will be noted that the loss values are almost exactly the same as those on 60 cycles under the same conditions and in every case are considerably less than 0.005. The same type of cell was placed in a d-c. circuit which was reversed every 24 hours. As might be ex-

TABLE I.

EFFECTS DUE TO VARIATIONS IN THE CIRCULATION OF THE ELECTROLYTE

60-Cycle Current
Wrought Iron Electrodes
1 per cent NaCl Solution Electrolyte

State of electrolyte	Total corrosion grams	Current ampere-hours	Coefficient of corrosion
Stirred	0.344	96	0.0034
Stationary	0.202	96	0.0020
Filter paper, separation	0.088	96	0.0009
Gelatin	0.074	96	0.0007
Stirred	0.065	160	0.0004
Sand saturated	0.016	160	0.0001

TABLE II.

EFFECTS DUE TO VARIATIONS IN THE CIRCULATION OF THE ELECTROLYTE

20-Cycle Current
Wrought Iron Electrodes
1 per cent NaCl Solution Electrolyte.

State of electrolyte	Total corrosion grams	Current ampere-hours	Coefficient of corrosion
Stirred	0.079	144.4	0.0005
Sand, saturated	0.009	144.4	0.00006

pected, the losses were very much greater, as shown by Table III; although the number of ampere-hours was considerably less than that used in the previous experiments. The electrode surrounded by the moving solution had a loss corresponding to a coefficient of corrosion of 0.45, while the other gave 0.32, the difference due to stirring thus being even more evident on the slow reversals than on the high frequencies. If only the current discharged by each electrode as anode were considered, the coefficient of corrosion in the stirred solution was 0.90, and that in the confined electrolyte was 64 per cent.

TABLE III.

EFFECTS DUE TO VARIATION IN THE CIRCULATION OF THE ELECTROLYTE.

24-Hour Reversals
Wrought Iron—Electrodes
1 per cent NaCl Solution Electrolyte.

State of electrolyte	Electrolytic corrosion grams	Current ampere-hours	Coefficient of corrosion
Stirred........................	45.45	97.1	0.45
Sand, saturated................	32.45	97.1	0.32

The foregoing results show that the free circulation of the electrolyte has a pronounced effect on the coefficient of corrosion, and that this effect is greater the lower the frequency of alternation of the current. They show that the low corrosion coefficient on alternating current is not determined solely by the speed of the reactions and the frequency of alternations. A more probable explanation is that the corrosion during any half cycle in which the electrode is anode takes place in accordance with Faraday's law, as in the case of direct current, but that during the succeeding half-cycle when the electrode is cathode a large part of the corroded metal is electroplated back on the electrode. The increased corrosion due to circulation of the electrolyte would be expected under this theory, since the convection currents in the liquid would carry away from the electrode surface a part of the metal that has been corroded during the half of the cycle when the electrode is anode, thus preventing as complete a redeposition during the succeeding half-cycle as would otherwise occur. In particular these convection currents in the electrolyte would bring into contact with the metallic ions, oxygen or other chemicals which would tend to form insoluble compounds, thus rendering the corrosive process irreversible.

Accepting the above theory, we would expect that in the case of iron or lead buried in soils, in which circulation of the electrolyte is greatly restricted, the corrosive process would be in large degree reversible even with much longer periods of reversal than in the case of liquid electrolytes, and it seemed possible that this condition might prevail even where the period of the cycle is several minutes or longer, as in the case of the polarity of buried pipes in many localities as mentioned above. This was found to be actually the case, as the following described experiments show.

COMPLETE SERIES OF TESTS

(*a*) *Arrangements*. With the results of the above experiments in view a more complete series of tests was planned. Since there is considerable variation among individual specimens, it was recognized that quite a number of specimens under each frequency would be necessary in order to get a fair average. The specimens were arranged in cells having two current-carrying electrodes and one specimen subjected only to soil corrosion, this specimen being protected from the flow of current by a glass cyclinder as shown in Fig. 3. In a few cases the effect of adding sodium carbonate to the soil was studied. For convenience the greater part of the tests were made in jars in the laboratory, but a number were made in specimens buried in soil out of doors in order to check the results obtained in the laboratory. The agreement between the results under the two conditions was found to be satisfactory. The entire series is outlined in Table IV.

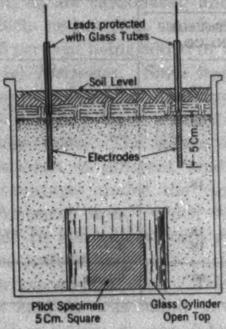

FIG. 3

(*b*) *Electrolyte*. In determining the coefficient of corrosion with different frequencies of current reversal it is desirable to simulate operating conditions as nearly as is feasible in a complete and general test. For this reason soil was selected as the electrolytic medium rather than water which contains the soluble constituents found to exist in soil by chemical analysis. Conditions of circulation of the electrolyte and the electrolytic transfer in it are very different than in soil. The soil used was natural soil near the Bureau of Standards—a light clay having a resistance of 8000 ohms per centimeter cube at approximate saturation. It will support a good vegetable growth and is a fairly normal soil. Soil from the same locality was used in the experiments described in a previous Bureau of Standards report[6] and a coefficient of corrosion of 100 obtained on iron at a definite current density.

TABLE IV.
SUMMARY OF TESTS.

a. Dimensions of Electrodes.

Electrodes	Indoor	Outdoor
Iron	5 x 5 x 0.5 cm.	20 x 20 x 0.2 cm.
Lead	5 x 5 x 0.2 cm.	15 x 15 x 0.4 cm.

b. Frequencies Used and Number of Specimens Used for both Iron and Lead.

Frequency of reversal	Number of specimens			
	Indoor		Outdoor Tests	
	Natural Soil	Soil with Na_2CO_3		
60 cycles per sec.	18	18	3 large	Iron only.
15 cycles per sec.	18			
1-sec. cycle	18	18	3 "	
6-sec. cycle	18			
1-min. cycle	18			
5-min. cycle	18			
10-min. cycle	18	18		
1-hr. cycle	18			
2-day cycle	18			
2-week cycle	18	18		
Direct current	18	18	3	
Totals	198	90	9 large	

Grand total for iron	297
" " " lead	291
" " " all tests	588

(*c*) *Conditions of the Tests*. Some of the tests were run in the soil out of doors with natural drainage and aeration. Although it was considered very desirable to make a number of such tests, to run a complete series in outside soil would have been very difficult on account of interference by weather, difficulty of getting electrical connections to many electrolytic cells, and especially the insulating of the various sets from each other, which would be necessary in order to determine the current actually entering or leaving each specimen. The cells used in the inside laboratory tests were 1-gal. (3.8-liter) earthenware jars filled with soil to about 3 cm. from the top (about 3 kg.) kept practically saturated by adding a quantity of distilled water every day. The tops were left open that evaporation and aeration might go on in a normal way.

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[6] McCollum and Logan; Technologic Paper No. 25. Electrolytic Corrosion of Iron in Soils.

(*d*) *Chemicals.* Since some soils vary widely in chemical constituents and these may have a pronounced effect on the rate of corrosion, it seems desirable to vary those constituents in the soil which may be expected to affect the corrosion. As indicated by preliminary tests, sodium carbonate (Na_2CO_3) has a very considerable effect on the electrolytic corrosion of both iron and lead; moreover sodium is a common element in soil, as are carbonates; and this combination is quite soluble, which makes it a satisfactory compound to use in the soil, 0.5 per cent being added to certain cells, as shown in Table IV.

Vol. 35
916

(*e*) *Electrodes.* Since iron and lead are the two metals commonly serving as underground electrical conductors exposed to soil they were selected as the materials for specimens in these tests. The above mentioned report shows that the corrosion of different kinds of iron does not differ by large percentages under the conditions of these tests, and since "American iron," which is Bessemer process steel, is obtainable in convenient form it was adopted. This material was fine-grained and quite pure, having about one-tenth per cent carbon and no slag. The lead was commercially pure and on analysis was found to contain traces of tin or antimony. Indoor specimens were 5 by 5 cm. square, the iron being about 0.5 cm. thick and the lead 0.2 cm. thick. The outdoor iron specimens were 20 cm. square and about 0.2 cm. thick.

The mill scale and oxide left on the materials in the process of manufacture were not removed, since it was felt that with alternating current the surface might affect the corrosion considerably more than with direct current. The leading-in wire was soldered to a corner of each specimen and a number stamped on the same corner. It was then weighed and a glass tube put over the lead and the tube was then sealed with pitch and the lead attachment and number covered with the same material. This type of connection failed in very few instances due to corrosion and the tube and pitch were easily removed with toluol before the specimen was reweighed.

(*f*) *Frequency*. In determining the frequency of reversal of current two things must be considered: first, the frequencies found in practise; and second, the completeness of the series so that a suitable curve could be obtained showing the relation between the corrosion coefficients and the frequency of reversal of current. The standard lighting frequency, 60 cycles is available, and 15 cycles adopted as about the lowest frequency proposed for power work. To obtain the slow reversals a reversing commutator machine was built which is described in detail later. It gave periods of one second, 6 seconds, 1 minute, 5 minutes, 10 minutes, and 1 hour. The short periods of reversal were adopted because reversals of polarity of such frequencies commonly occur in the usual operation of a street railway system as pointed out above. Daily and weekly reversals and d-c. tests were also made. The d-c. specimens serve as a check on the theoretical coefficient of corrosion.

(*g*) *Current Density*. The current density flowing to or from the plates was intended to be such as to produce approximately 100 as the coefficient of corrosion with d-c. electrolysis. This is shown in Technologic Paper No. 25 of the Bureau of Standards above referred to, to be about 0.5 milliampere per sq. cm. for iron and approximately this value was used on both the indoor and outdoor specimens.

(*h*) *Length of Run*. The tests were contined until enough effect was produced to permit of accurate determination of the differences in weight of the specimens before and after test. It was also intended that one of the tests should be continued until a state of equilibrium was reached in the cell; that is, until the rate of corrosion was not changing rapidly as might be the case during the first few cycles of current. Moreover, the cells should not be run to an exhaustion of the soluble chemicals, their concentration being probably closely related to the amount and rate of corrosion occurring on the electrodes. Since the current density is the same in all cases, this rate will depend on the frequency of reversal, and since the coefficient of corrosion is less on the higher frequencies these must run fully as long as the lower frequencies in order to obtain sufficient weight differences. A period of 15 to 20 days has been found to produce sufficient differences in weight, and no indication that the composition of the soil, except that very close to the electrodes, had been changed decidedly.

(*i*) *Accidental Variables.* Other possible variables that received attention during the experiments were maintained as nearly constant as possible. The temperature did not vary widely from 20 deg. cent. there being very little heating by the current at the voltage and current density used. The depth was maintained about 10 cm. below the surface in the indoor tests and about 40 cm. in those outside the laboratory.

(*j*) *Cleaning Electrodes.* After each run was completed it was necessary to remove the end products of the corrosion process, and since they adhered firmly in some cases special methods were necessary. Iron specimens were cleaned by making them cathode on a ten volt circuit in a two per cent sulphuric acid solution, as described in Technologic Paper No. 25 of the Bureau of Standards. This was found to be very effective and did not attack the iron enough to show on the balances used. The lead specimens were cleaned by immersing them in a solution containing 5 per cent oxalic acid and 1½ per cent of nitric acid. The corrosion products became lead oxalate—a white flocculent substance which was easily removed by brushing. It was found in some cases where the amount of corrosion was large and adhered very firmly that this process was very slow and did not remove the corroded products entirely. Unoxidized specimens weighed before and after immersion in this lead cleaning solution were found to have lost less than 5 milligrams, the limit of the balances used.

EQUIPMENT

(*a*) *Current Sources.* Sixty-cycle current was obtained from the city power mains, while the 15-cycle current came from a small inverted synchronous converter. Transformers were used in both circuits to raise the voltage so that a number of cells could be operated in series and so that the primary side would be clear of ground. For the slower reversals of current on the indoor tests power was obtained from the regular three-wire lighting busbar and commutated by the machine described below. For the outdoor tests for slower reversals and for direct current a small motor-generator set was used. A no-current indicator was used on the a-c. circuits while a recorder showed what had occurred on the d-c. circuit and those of long period at all times.

(*b*) *Commutating Machine.* The commutating machine through which the intermediate frequencies were obtained consisted of a series of six commutators each having four brushes and two equal semi-circular commutator segments, giving two complete cycles per revolution, driven by gears having such ratios that with the first or highest speed commutator rotating once in two seconds the succeeding commutators made complete current cycles in six seconds, one minute, five minutes, ten minutes, and one hour. This machine was driven by a constant speed motor.

(*c*) *Resistance.* In order to obtain the correct current density discharged from the electrodes the resistance of the circuits had to be varied. This was done in part by placing cells in series in groups and paralleling these groups. Rheostats or tungsten lamps were then used to get final adjustments, but no great effort was made to keep the current discharge at exactly 0.5 milliamperes per sq. cm., since a small variation in current density does not affect the rate of corrosion. Tungsten lamps with their high positive temperature coefficient are very satisfactory for use in such circuits, since within a certain range they tend to automatically maintain the current at a constant value.

(*d*) *Current Measurements.* Observations of current were made every day, and more frequently when the current values were changing appreciably. A standard milliammeter having a resistance of 0.34 ohm was used for all frequencies above one second. For a-c. measurements a thermo-ammeter consisting of a heating element, thermo-couple and millivoltmeter was used. The resistance of this meter amounted to about 7 ohms, and was non-inductive. When this meter was introduced in circuits the effect on the current flow was negligible because of the high resistance of the circuits and it was very easy to correct for this small non-inductive resistance by inserting an equal amount in each circuit when the meter was not in use. This meter was used to measure larger currents in the outdoor specimens by means of a shunt. A suitable ampere-hour meter was not available.

Correction and Reduction Factors

Since chemical corrosion, according to Faraday's law, is proportional to the average current flowing, and since all a-c. values as observed are effective values rather than average, the current flow has been corrected by dividing the same by 1.11, the ratio between effective and average values of sine-wave current. Since the current flowing with the longer time reversals is controlled by a commutating machine or switch the wave is flat-topped and no such correction is necessary. However, the current was off when controlled by the commutating machine, 6 or 7 per cent of the time and this correction was applied to all such values. In order to correct any error due to a possible difference in the length of succeeding half cycles, the connections to the commutator controlling each test were reversed at regular intervals, *e.g.*, the one-second commutator was reversed through the 10-minute commutator and the one-hour one by a switch every 24 hours. In calculating the theoretical amount of corrosion, the corrosion products of both iron and lead were taken to be divalent and the quantity corroded per ampere-hour is then 1.04 grams for iron and 3.86 grams for lead.

ACCURACY OF RESULTS

The accuracy which can be obtained in corrosion experiments of this kind is limited by a number of factors; first, the consistency of the corrosion action itself, which it has been found may vary within wide limits under apparently similar conditions; and second, the limits of measurement. The electrical measurements are correct to about one per cent while the time measurements are not in error more than a half per cent. The error due to weighing of single specimens was small, since it was carried to the fourth or fifth place, but in some cases the losses were small and this difference was correct to only the second or third place. This is true of practically all pilot specimens which were subjected only to natural corrosion. Therefore it is evident that the accuracy of the results is greater when the amount of corrosion is large. The combined accuracy of all measurements was much greater than the consistency to be expected in the corrosive processes.

DESCRIPTION OF EACH RUN

The above description of the general condition of the tests is intended to apply to all the following data, and it will be necessary to describe each run only very briefly, deferring until later the presentation of the results.

(*a*) *Sixty-Cycle Tests.* The 60-cycle tests were run with both iron and lead specimens on the indoor tests and iron for the outdoor tests. Both natural soil and soil with 0.5 per cent sodium carbonate added were used for the indoor tests. It will be noted from the tables presented below that in this as well as in other runs the natural corrosion losses have been rather large on the iron pilot specimens. This is due to the fact that the mill scale was not removed from these specimens before the tests were started and that the cleaning process removed this scale as well as the oxide that was formed during the test. This rather obscures the comparative effect of natural soil and sodium carbonate, but it is still evident as in the earlier tests that the natural corrosion loss of iron is greater in natural soil while the electrolytic corrosion is greater in the chemical soil. In fact in almost every instance the natural loss was greater than the electrolytic loss in the natural soil, and in five of the twelve specimens also in the chemical soil. With the three large specimens used in the outdoor tests the natural loss was considerably less than the electrolytic loss, and the coefficient of corrosion is only slightly less than one per cent.

(*b*) *Fifteen-Cycle Tests.* The 15-cycle tests were run with lead and iron in soil only, these cells being in series with about 310 volts, giving about 25 volts per cell. In every case except four iron electrodes the electrolytic losses were all greater than the natural corrosion in the same cells.

(*c*) *One-Second Period.* Iron and lead specimens in both normal soil and soil with sodium carbonate were used in the tests with one-second period, the cells being divided into four groups of three each in series. In two cases the iron electrodes lost more than the pilot specimens but on the average the losses were greater than in the preceding tests. Iron specimens were placed in outdoor soil for these tests, and in this instance the natural corrosion is unusually high because the specimens were left in the ground without current for a considerable time.

(*d*) *Six-Second Period.* Normal soil alone was used in these tests, there being three groups of cells and four cells in each group. Approximately 12.5 volts existed across each cell in order to maintain the current at about 30 milliamperes or 0.5 milliamperes per sq. cm.

(*e*) *One-Minute Period.* In the one minute reversals iron and lead electrodes were used in natural soil connected in three groups of four cells each. Approximately nine volts were maintained across the cells containing the iron electrodes and 14 volts on the lead electrodes. In case of the iron electrodes there was a consistently greater loss on the odd electrode than on the even; the reason for which is not altogether evident since no such consistency exists on the lead specimens; and as the two sets were in series, it is therefore not due to unbalanced or unequal half cycles.

(*f*) *Ten-Minute Period.* Both iron and lead specimens in natural soil and soil containing sodium carbonate were used in the ten-minute period tests. The cells were divided into four groups of six each. It will be noted that the corrosion of iron in natural soil is here greater than in the chemical soil and the reverse is the case with the lead specimens.

(*g*) *One-Hour Period.* Only natural soil was used in the one-hour reversals, about 15 volts being impressed on each pair of electrodes.

(*h*) *Forty-Eight-Hour Period.* Natural soil alone was used in the daily reversals (48-hour period) with iron and lead electrodes, the entire set being in series on 240 volts. The iron specimens had a voltage of about 15 volts on each pair and the lead electrodes about 13 volts. In the case of the iron specimens the odd and even specimens, or those anode first or anode last in the test show no great or consistent difference as noted in the preliminary tests, and the lead specimens show an opposite effect from that noted at that time, that is, the electrodes which were anode during the first half-cycle have lost more than those which were cathode initially.

(*i*) *Weekly Reversals.* Both natural soil and soil containing sodium carbonate were used in the weekly reversals (2-week period) and the entire set was connected in series on 240 volts. The voltage across the iron specimen cells in the natural soil was about 15 volts per cell and about 9 volts in the chemical soil. With the lead electrodes the average voltage was less than 12 across each cell in the natural soil and less than 4 in the chemical soil.

(*j*) *Direct-Current Tests.* The d-c. tests were carried on with iron and lead specimens both indoors and outdoors and in the indoor tests with sodium carbonate in the soil as well as natural soil. The indoor cells were connected in four groups of six each with 230 volts impressed on them. The ampere-hours varied in the different groups from eight to twelve. With the iron specimens the anode losses are large, the coefficient of corrosion being approximate unity, while the cathode specimens lost less than the pilot specimens, evidently because of the protective effect of the current. In the lead specimens, however, the anode losses are far below what might be theoretically expected, while the cathodes lost less in the natural soil than the pilot specimens but more in the soil containing sodium carbonate. This is due not so much to an increased electrolytic loss in the chemical soil, but to a greatly decreased natural loss. Since the loss in the lead specimens was so much less than might be expected another set was run under practically the same conditions but with the current maintained more closely at 0.5 milliampere per sq. cm. These results, however, corroborate the work previously done. The outdoor tests were conducted on both lead and iron with the large plates mentioned above. The protective effect of the current is noted again on the iron specimens. In the lead specimens twelve anodes were used, the lead in this case being sections of lead sheath cable, six of which contained about one per cent antimony while the other six contained only traces of tin and antimony. Two pilot specimens of each composition were used. These tests further corroborated the results of the indoor tests in that the coefficient of corrosion of lead with direct current was low.

Discussion of Results

Tables containing the summary of the results of the above mentioned tests are given below. These tables are arranged in halves with losses in grams above and the coefficient of corrosion below with the frequency or period of reversal in the first column, the average loss of six specimens in each of the three succeeding columns (the first being the odd numbered electrodes and the second the even numbered electrodes and the third the pilot specimens.) From these are calculated the electrolytic loss of odd or even electrodes shown in the fifth and sixth columns, and the seventh column contains the average electrolytic loss of all electrodes. Below the frequency is repeated and the next column contains the average quantity of electricity in ampere hours flowing through the specimens. Following this are four columns giving the coefficient of corrosion. The coefficients of corrosion of the odd electrodes and even electrodes are first given, then the coefficient of corrosion based on one-half the current or that while each electrode was positive, and last, that based on the average loss and the total current through the cells. Since it is difficult to draw any conclusions from the electrode losses shown without also considering the ampere-hours, the coefficients of corrosion will give us the best idea of results, and these are shown in both the tables and curves.

TABLE V

SUMMARY OF ALTERNATING-CURRENT ELECTROLYSIS TESTS—I.

Variable—Frequency of Reversal.

Indoor Tests
Iron Electrodes
Soil Electrolyte.

Period	Total loss			Electrolytic loss		
	Odd electrodes	Even electrodes	Pilot	Odd electrodes	Even electrodes	Average
	Grams	Grams	Grams	Grams	Grams	Grams
60 cycle	1.480	1.289	1.645	−0.165	−0.356	−0.261
15 cycle	1.036	0.862	0.834	+0.202	+0.028	+0.115
1 sec.	1.064	1.190	0.640	0.424	0.550	0.488
6 sec.	0.960	1.046	0.566	0.394	0.480	0.437
1 min	2.024	2.077	1.203	0.821	0.874	0.848
5 min	1.907	1.398	0.748	1.159	0.650	0.904
10 min	2.522	2.252	0.901	1.621	1.351	1.486
1 hour	3.134	2.941	1.165	1.969	1.776	1.872
2 days	5.490	5.124	1.130	4.360	3.994	4.177
2 weeks	8.349	9.680	1.387	6.962	8.293	7.627
D. C.	9.697	0.139	1.023	8.674		8.674

Period	Current discharge ampere-hrs.	Coefficient of corrosion			
		Odd electrodes	Even electrodes	Average ½ current	Average total current
60 cycle	16.05	−0.0198	−0.043	−0.031	−0.0156
15 cycle	13.32	+0.0292	+0.0004	+0.016	+0.008
1 sec.	17.99	0.045	0.059	0.046	0.023
6 sec.	16.83	0.045	0.055	0.050	0.025
1 min.	19.25	0.082	0.087	0.084	0.042
5 min.	19.99	0.111	0.063	0.087	0.043
10 min.	16.48	0.189	0.158	0.173	0.087
1 hour.	18.40	0.206	0.186	0.197	0.098
2 days.	27.22	0.308	0.282	0.295	0.148
2 weeks.	23.17	0.58	0.69	0.633	0.316
D. C.	9.82	0.85			0.850

(*a*) *Indoor Tests. Iron in Normal Soil.* In Table V a summary of the results obtained using iron electrodes in indoor cells containing normal soil are given. As mentioned earlier, it will be seen that the pilot specimen loss is quite large and that there is considerable variation under the different frequencies. This is evidently a real variation due to a difference in soil action because it was found that in individual cases when the pilot specimen corrosion varied considerably from the average the current-carrying electrodes would also vary in the same direction. The coefficient of corrosion only in the case of the 60-cycle tests is negative. The electrodes were numbered consecutively, an odd number and a succeeding even number being grouped in each cell. The difference in the coefficient of corrosion between the odd and even electrodes is rather large in some cases; for example, in the 5-minute specimens the coefficient is 0.111 for the odd electrodes and only 0.063 for the even and in the 15-cycle test, the per cent discrepancy is large, although the values in grams do not differ greatly. The d-c. test shows a coefficient of only 0.85 which is rather low, and this can only be explained as being probably due to the effect of the iron oxide serving as a protection rather than accelerating the corrosion. The next to the last column is simply double the one succeeding or an average of the odd and even electrode coefficients.

(*b*) *Indoor Tests. Iron Electrodes in Soil with Sodium Carbonate.* In Table VI containing the results on iron electrodes in sodium carbonate soil it will be noted that in the case of the 60-cycle run the coefficient of corrosion is positive but that the values in the other cases of reverse currents are smaller than in the natural soil. In the two-weeks test the odd-electrode loss is considerably less than the even, supporting the theory that in these longer time reversals the electrodes which are positive last suffer the greater loss. Under these conditions the d-c. loss is very nearly 100 per cent.

(*c*) *Indoor Tests. Lead Electrodes in Soil.* With lead electrodes in soil very regular results were obtained. In Table VII the loss is shown to be increasing gradually from 60 cycles to 2 weeks with only one discrepancy, the even electrode in two-day reversals being considerably smaller than on the 10-minute and 1-hour specimens. The products of corrosion seem to be increasing the effect on the pilot specimens, as it will be noted that the loss is increasing as the frequency decreases. However, the most remarkable facts concerning these tests is that the odd electrodes, those which were initially positive in the tests, lost considerably more than the even electrodes in both the two-day and two-weeks test. The other remarkable feature is the small coefficient of corrosion exhibited in the case of the d-c. test. Since in the first set weighed the losses were so small, (only 22 per cent of the theoretical) a second run was made and a coefficient of 0.25 obtained, practically the same as before. This indicates that under the conditions of these tests and probably under most soil conditions the corrosion of lead is very considerably less than it has been formerly considered to be.

TABLE VI.

SUMMARY OF ALTERNATING-CURRENT ELECTROLYSIS TESTS—II.

Variable—Frequency of Reversal.

Indoor Tests
Iron Electrodes
Soil and Sodium Carbonate Electrolyte.

Frequency of reversal	Total loss			Electrolytic loss		
	Odd electrodes	Even electrodes	Pilot	Odd electrodes	Even electrodes	Average
	Grams	Grams	Grams	Grams	Grams	Grams
60 cycle	1.390	1.373	1.199	+0.191	0.174	+0.182
1 sec.	0.865	1.146	0.677	0.188	0.469	0.329
10 min.	1.617	1.532	0.835	0.782	0.679	0.739
2 weeks	7.922	9.081	1.636	6.286	7.451	6.868
D. C.	10.423	0.172	0.819	9.604		9.604

Frequency of reversal	Current discharge ampere-hrs.	Coefficient of corrosion			
		Odd electrodes	Even electrodes	Average ½ current	Average total current
60 cycle	16.05	0.023	0.021	0.022	0.011
1 sec.	17.99	0.020	0.050	0.035	0.018
10 min.	16.48	0.091	0.081	0.086	0.043
2 weeks	23.17	0.52	0.62	0.57	0.285
D. C.	9.82	0.94			0.94

(*d*) *Indoor Tests. Lead Electrodes in Sodium Carbonate.* The losses of lead electrodes in sodium carbonate (Table VIII)

TABLE VII

SUMMARY OF ALTERNATING-CURRENT ELECTROLYSIS TESTS—III.

Variable—Frequency of Reversal

Indoor Tests
Lead Electrodes
Soil Electrolyte.

Frequency of reversal	Total loss			Electrolytic loss		
	Odd electrodes	Even electrodes	Pilot	Odd electrodes	Even electrodes	Average
	Grams	Grams	Grams	Grams	Grams	Grams
60 cycle	0.325	0.328	0.124	+0.201	+0.204	0.202
15 cycle	0.342	0.332	0.133	0.209	0.199	0.204
1 sec	0.385	0.354	0.118	0.267	0.236	0.252
6 sec	0.518	0.528	0.098	0.420	0.430	0.425
1 min	2.860	2.845	0.652	2.208	2.193	2.200
5 min	3.868	3.634	0.406	3.462	3.228	3.345
10 min	3.468	3.738	0.341	3.127	3.397	3.262
1 hr	5.886	5.771	0.901	4.985	4.870	4.928
2 days	8.719	5.072	1.357	7.362	3.715	5.538
2 week	13.710	7.789	1.176	12.634	6.713	9.674
D. C.	12.319	0.327	0.937	11.382		11.382
D. C.	13.574	0.277	0.882	12.692		12.692

Frequency of reversal	Current discharge ampere-hrs.	Coefficient of corrosion			
		Odd electrodes	Even electrodes	Average ½ current	Average total current
60 cycle	16.05	0.0065	0.0066	0.0065	0.0033
15 cycle	13.32	0.0082	0.0077	0.0080	0.0040
1 sec	14.87	0.0093	0.0082	0.0088	0.0044
5 sec	16.83	0.0129	0.0132	0.0131	0.0065
1 min	19.25	0.059	0.059	0.059	0.030
5 min	19.99	0.089	0.085	0.086	0.043
10 min	14.95	0.108	0.118	0.112	0.056
1 hour	18.40	0.140	0.137	0.139	0.069
2 day	27.22	0.140	0.071	0.105	0.053
2 week	23.17	0.282	0.150	0.216	0.108
D. C.	13.40	0.220			0.220
D. C.	12.93	0.254			0.254

are greater than in the normal soil, the difference being especially noticeable in the longer reversals and in the d-c. tests. For example, in the weekly reversals, the loss in normal soil was 0.108 while in the sodium carbonate it was 0.172; the d-c. loss has risen from about 25 per cent to 34 per cent.

TABLE VIII.

SUMMARY OF ALTERNATING-CURRENT ELECTROLYSIS TESTS—IV.

Variable—Frequency of Reversal

Indoor Tests
Lead Electrodes
Soil and Sodium Carbonate Electrolyte.

Frequency of reversal	Total loss			Electrolytic loss		
	Odd electrodes	Even electrodes	Pilot	Odd electrodes	Even electrodes	Average
	Grams	Grams	Grams	Grams	Grams	Grams
60 cycle.........	0.555	0.542	0.077	0.478	+0.465	0.471
1 sec............	0.316	0.630	0.062	0.254	0.568	0.411
10 min.........	4.019	3.844	0.110	3.909	3.734	3.822
2 weeks.........	17.356	13.487	0.111	17.245	13.370	15.307
D. C...........	17.726	0.428	0.075	17.651		17.651

Frequency of reversal	Current discharge ampere-hrs.	Coefficient of corrosion			
		Odd electrodes	Even electrodes	Average ½ current	Average total current
60 cycle.........	16.05	0.0154	0.0150	0.0152	0.0076
1 sec............	14.87	0.0088	0.0198	0.0143	0.0071
10 min.........	14.95	0.135	0.129	0.132	0.066
2 weeks.........	23.17	0.386	0.299	0.344	0.172
D. C...........	13.4	0.340			0.340

(*e*) *Outdoor Tests. Iron and Lead Electrodes in Soil.* The outdoor tests shown in Table IX are not extensive, but the cases given show reasonably good agreement with the indoor tests given above. The coefficient of corrosion at 60 cycles is slightly less than 0.01 for iron electrodes and the d-c. loss is 0.70. Considering only the d-c. tests on iron, it was noted that as the voltage necessary to maintain the current at 0.5 milliampere per cm. became greater the coefficient of corrosion decreased. For example, we find a coefficient of corrosion of 0.96 for iron electrodes in sodium carbonate soil and 0.85 in normal soil on the indoor tests and only 0.70 for the outdoor tests and the potential has varied from about 10 volts on the first to 35 on the last test.

TABLE IX.

SUMMARY OF ALTERNATING-CURRENT ELECTROLYSIS TESTS—V.

Variable—Frequency of Reversal.

Outdoor Tests
Iron and Lead Electrodes
Soil and Sodium Carbonate Electrolyte.

Frequency of reversal	Total loss			Electrolytic loss		
	Odd electrodes	Even electrodes	Pilot	Odd electrodes	Even electrodes	Average
	Grams	Grams	Grams	Grams	Grams	Grams
60 cycle....	2.65	2.60	0.97	1.68	1.63	1.65 Iron
1 sec.......	9.06	7.30	5.94	3.12	1.36	2.24 Iron
D. C.......	41.96	1.73	4.61	37.35	37.35	37.35 Iron
D. C.......	871.861		6.216	865.645		865.645 Lead

Frequency of reversal	Current discharge ampere-hrs.	Coefficient of corrosion			
		Odd electrodes	Even electrodes	Average $\frac{1}{2}$ current	Average total current
60 cycle.......	165.4	0.0203	0.0197	0.0192	0.0096 Iron
1 sec..........	102.	0.0589	0.0256	0.0431	0.0215 Iron
D. C..........	51.6	0.700	0.700	0.700	0.700 Iron
D. C..........	1034.	0.217	0.217	0.217	0.217 Lead

CURVES

The data shown in the above tables have been plotted in curves in which the ordinates are coefficients of corrosion expressed in per cent and the abscissas are the logarithms of the number of seconds required for one complete cycle. Fig. 4 shows the data obtained with iron electrodes, these being based on the average electrode loss and the total current flowing in any one direction through the cells. The coefficient is therefore based on the total current discharged by one electrode. It will be noted that the curve for the coefficient in natural soil is above that for soil containing sodium carbonate except the last point for direct current when the latter shows the greater loss. The values begin to rise quite rapidly at about the 10-minute cycle and reach a maximum in the d-c. test, the value for which is placed arbitrarily as far as the time is concerned. It is very interesting to note that even in the case of a cycle of two weeks duration the coefficient of corrosion is only about 0.6 and on a 2-day cycle only 0.3 of its value for direct current.

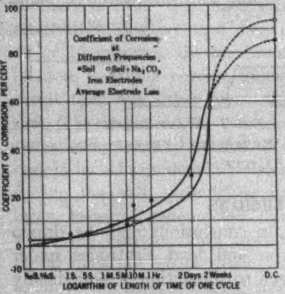

FIG. 4

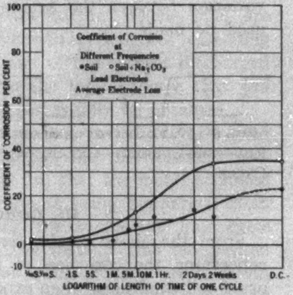

FIG. 5

Fig. 5 contains the same data on lead electrodes and here it is seen that the soil containing sodium carbonate produces a consistently higher coefficient of corrosion than the natural soil, just the reverse of the condition with iron electrodes. The tendency to rise is noticed at an earlier point or a higher frequency than with the iron, beginning with about the one-minute cycle, and at a cycle of two weeks duration the coefficient of corrosion has reached the same value as for direct current.

SUPPLEMENTARY TESTS

Since certain authors have pointed out the fact that the wave form of alternating current is affected when passing through an electrolytic cell, and since a material change in such wave form would affect the current measurements, an oscillograph was used to determine the wave form of current passing through the cell and its relation to the potential wave impressed on it. It was found that there was no appreciable distortion of the wave shape due to the presence of the cell.

In order to determine the cycle of operation of the commutating machine exactly, the current wave was observed with the oscillograph. It is seen that on the one-second cycle, Fig. 6, the current increases slightly during about the first $\frac{1}{4}$ second and falls during the remainder of the half-cycle. In the six-second cycle, Fig. 7, this rise and fall is seen and the fall continues for a considerable part of each half cycle, but the waves appear to be so nearly flat top in both the 1-second cycle and the six-second cycle that no correction due to the variation between the average value and the effective value need be made.

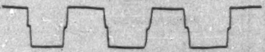

FIG. 6—WAVE SHAPE FOR SLOWLY REVERSED CURRENT—ONE-SECOND CYCLE

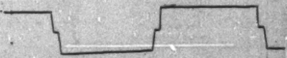

FIG. 7—WAVE SHAPE FOR SLOWLY REVERSED CURRENT—SIX-SECOND CYCLE

III. CONCLUSIONS

From the above results certain conclusions may be drawn concerning the corrosion of iron and lead electrodes under usual soil conditions when exposed to the action of periodically reversed current.

1. The corrosion of both iron and lead electrodes decreases with increasing frequency of reversal of the current.

2. The corrosion is practically negligible for both metals when the period of the cycle is not greater than about one minute.

3. With iron electrodes a limiting frequency is reached between 15 and 60 cycles per second, beyond which no appreciable corrosion occurs. No such limit was reached in the lead tests, although it may exist at a higher frequency than 60 cycles.

4. With periodically reversed currents, the addition of sodium carbonate to the soil reduces the loss in the case of iron and increases it in the case of lead.

5. The coefficient of corrosion of lead, under the soil conditions described in the report, when subjected to the action

of direct current was found to be only about 25 per cent of the theoretical value.

6. The corrosion of lead reaches practically the maximum value with a frequency of reversal lying between one day and one week.

7. The corrosion of iron does not reach a maximum value until the period of the cycle is considerably in excess of two weeks.

8. The most important conclusion to be drawn from these investigations is that in the so-called neutral zone of street railway networks where the pipes continually reverse in polarity, the damage is much less than would be expected from a consideration of the arithmetical average of the current discharged from the pipes into the earth. Where pipes are alternately positive and negative with periods not exceeding 10 or 15 minutes, the algebraic sum of the current discharged is more nearly a correct index to the total damage that will result than any other figure that can readily be obtained.

9. The reduction in corrosion due to periodically reversed currents appears to be due to the fact that the corrosive process is in a large degree reversible; so that the metal corroded during the half cycle when current is being discharged is in large measure redeposited during the succeeding half cycle when the current flows toward the metal. This redeposited metal may not be of much value mechanically, but it serves as an anode surface during the next succeeding half cycle, and thus protects the uncorroded metal beneath.

10. The extent to which the corrosive process is reversible depends upon the freedom with which the electrolyte circulates, and particularly, on the freedom of access of such substances as oxygen or carbon dioxide, which may result in secondary reactions giving rise to insoluble precipitates of the corroded metal. It is largely for this reason that the corrosion becomes greater with a longer period of the cycle since the longer the period the greater will be the effect of these secondary reactions.

DISCUSSION ON "THE INFLUENCE OF FREQUENCY OF ALTERNATING OR INFREQUENTLY-REVERSED CURRENT ON ELECTROLYTIC CORROSION" (McCOLLUM-AHLBORN), NEW YORK, MARCH 10, 1916.

Philip Torchio: The most important results in the findings in these investigations are, first, that with ordinary frequencies of 25 to 60 cycles, the corrosion of underground structures is, practically nil. In this country some of the water companies are still objecting to having the electric lighting companies ground their neutrals to the pipes of the water companies. I think that the results of the investigation of the Bureau of Standards should dissipate any fear of trouble due to the grounding of neutrals to the water pipes.

The next important point brought out by the paper, which should dissipate another fear, is that with potentials in a certain zone changing from positive to negative, which fluctuation may occur in periods represented by the passing of a car with time intervals of possibly five or ten minutes, the corrosion would be negligible.

The next important conclusion to be drawn from the paper is rather astonishing, in so far that only in this year of 1916 a paper of this character should be presented to the railway engineers seriously proposing to ameliorate electrolysis conditions by reversing the polarity of the trolley at certain intervals, as, for instance, of one hour, or a day, or even a week, and showing that by so doing the damage by electrolysis may be reduced to one-tenth, or one-quarter of what it would be by keeping the trolley potential constant, as we are accustomed to do.

Now, this suggestion of reversing the potential of the trolley is not a new one. It cannot be ascribed to ignorance, that this method has not been tried, because as far back as 1902 a Danish engineer, Mr. Absalon Larsen, published in the *Elektrotechnische Zeitschrift* of September 1902, the results of his tests made in the Copenhagen Polytechnic Laboratory; and also a field test, both carried out on practically the same lines as those carried out by Messrs. McCollum and Ahlborn. Making allowance for the immeasurably greater details and completeness of the investigation of Messrs. McCollum and Ahlborn, and also the more complete scientific methods of procedure, it is astonishing that the results obtained in Copenhagen fifteen years ago are in their broad general lines confirmed by the results of the work in the Bureau of Standards.

In Mr. Larsen's paper he states briefly, that the results are as follows: That with one reversal per day the electrolytic action can be reduced to one-quarter, and by one reversal per hour it can be reduced to one-thirtieth of its normal value. From the tables given in to-night's paper we see that the results with one reversal every two days would be in the order of one-quarter, and one reversal every hour would be in the order of one-tenth, and it is, therefore, broadly speaking, astonishing that in fifteen years no use whatsoever has been made of the suggestion presented by Larsen.

Two years ago the Joint National Committee on Electrolysis reported on European practise. I made a survey throughout certain of the European countries, and before starting from America I consulted with Dr. Rosa on what line of investigation I should follow, and on his suggestion I had prepared a list of questions to ask every gentleman I interviewed. As a result of all of the interviews I had in England, France, Germany and Italy, I found that this suggestion of the reversal of potential was practically never used. The only places where the potential of the trolley has been reversed were in St. Gall and Nürnberg, but that was done only once, to try to remedy electrolytic conditions. In all other cases practically no application has been made of this suggestion which appears to promise great benefit in many bad electrolysis situations.

Now, I would like to hear from railway engineers why this is so, why this suggestion, which undoubtedly has been known for fifteen years, has never been applied, and then what are the objections to applying it.

Alexander Maxwell: I think the authors of this paper should be congratulated for their investigation of this very practical phase of the general subject of corrosion of underground structures by stray currents, particularly with regard to that part of the investigation which deals with reversing continuous currents, as distinguished from alternating currents of the ordinary frequencies. It is too often assumed that serious corrosion occurs only where the affected structures are close to the rails and positive in potential to them, whereas corrosion is frequently found in the so-called "neutral zones" as well as in locations remote from railway structures, in the latter case corrosion being due to exchange of current between different piping or cable systems, very often associated with reversals of direction.

In one respect, however, I desire to offer a criticism which repeats a similar comment of mine in connection with an earlier paper of one of the authors, namely, that the current densities employed are much higher than those encountered in practise. To be sure, the authors have offered a good reason for the current density employed, but it seems especially unfortunate that lower densities were not investigated on account of the uncertainty which remains regarding the precise nature of the corrosion where low corrosion coefficients were found.

Two examples taken at random illustrate the magnitude of the apparent current densities which may be met in practise, associated with actual corrosion. In one case current having a 24-hour average value of 3.4 amperes, flowed from a 20-inch cast iron gas main between two test stations, 150 feet apart. This works out to 0.0046 milliampere per sq. cm., average, over the whole surface. Therefore, only about 1/100 of the whole surface would be conducting to attain the current density used in the experiments described in the paper.

In another case, serious damage was done to cable sheaths by the loss of one ampere in a single section between manholes. Since the cable was of large diameter, it may be assumed that the lowest 1-inch of circumference was in contact with moisture and soil in the conduit, the minimum distance between manholes was about 250 feet. Under these conditions, the contact area would be 19,350 sq. cm., and the average current density would be 0.052 milliamperes per sq. cm., or roughly, 1/10 of the value used in the paper.

I do not mean to say that densities as low as these average densities should necessarily be employed for experimentation, but that something approximating them should be employed in view of the admitted influence of secondary effects which greatly increase the corrosion coefficients at low densities, and which might strongly influence an investigation like the present one. Moreover, it should be borne in mind that the average current densities referred to above may still be directly compared with the densities used by the authors, since theirs are also average densities.

A. F. Ganz: Several papers have been published describing the results of experiments with alternating currents of commercial frequencies in producing electrolysis of iron in soils and in solutions. The results of these experiments have generally shown that with alternating current some corrosion results, but that this is only of the order of one per cent of that calculated by Faraday's law from the quantity of electricity discharged from the anode. The present authors have found substantially the same results with alternating currents of frequencies of 15 and 60 cycles per second. The authors have also included tests using direct current which was reversed at relatively long intervals, the periods varying from one second to two weeks. They have found that even with the longest period of reversal, the corrosion produced is less than that computed by Faraday's law from the total quantity of electricity leaving the anode, and that the corrosion of both iron and lead electrodes decreases with increasing frequency.

The authors have used a current density of approximately 0.5 milliampere per sq. cm. for the iron and also for the lead samples, which is approximately 0.46 ampere per sq. ft. This current density is probably over 10 times as great as is generally found in practise in the case of pipe and cable sheaths affected by stray currents. The authors state that this current density was used because in a previous investigation on the corrosion of iron in street soils, it had been found that with current densities no greater than these, coefficients of corrosion of practically unity were obtained with direct current. I would like to ask the authors whether in the case of lead, similar tests were made, and if so, whether with much smaller current densities, a coefficient of corrosion as low as 25 per cent was also found. It is well known that as the density of current flowing from a corrodible anode to an electrolyte is increased, a point is reached where, in addition to the metal going into solution, gases are formed so that only part of the electricity is effective in dissolving the anode, and the other part produces gas. If tests with lower current densities on lead samples have not been made, it seems to me that this should be done before the conclusion can be accepted that with lead as an anode the corrosion is only 25 per cent of that calculated by Faraday's law.

The present tests were made with only one kind of soil. It is entirely possible also that with soils containing other constituents than the soil used, a higher coefficient of corrosion may be found for lead.

Assuming, however, that the corrosion from electrolysis with lead anodes is under practical conditions only 25 per cent of that calculated by Faraday's law, it seems to me that this makes alternating or infrequently reversed currents much less advantageous in the case of lead than is indicated by the coefficients of corrosion given for these currents in the paper. To make clear what I mean, I find in Table VIII that with a frequency of reversal of 10 minutes, the average coefficient of corrosion is given as 0.132. This figure is obtained by dividing the actual loss from electrolysis by the loss calculated by Faraday's law. If, however, with direct current the coefficient of corrosion is 25 per cent instead of 100 per cent, the beneficial effect of a frequency of reversal of 10 minutes is represented by four times 0.132 or by 0.528, and not by 0.132. This means practically that if with direct current a certain amount of corrosion is produced, a reversing current having a frequency of 10 minutes will cause a little more than half as much corrosion as the direct current. As it is well known that lead cable sheaths in practise are very rapidly destroyed by localized pitting where they are at all times positive to earth, and even where a relatively small current flows from the cable sheaths, it is evident that much less improvement is to be expected from alternating or from infrequently reversed currents in the case of lead cable sheaths than is indicated by the coefficients of corrosion given in the paper.

The authors state that the reduction in electrolytic corrosion from alternating or infrequently reversed currents appears to be due to the fact that the corrosive action is in a large degree reversible. While the results of the tests indicate that this may be the action, I do not believe that they are sufficiently conclusive to prove this theory, and it would be very desirable to have this phase of the subject discussed theoretically from an electrochemical standpoint. This is to my mind extremely important because it may serve to answer the question as to whether the low coefficients of corrosion found in the present tests may also be expected with the widely varying conditions of the electrolyte found in practise.

On the basis of the very low coefficients of corrosion found where the reversal is one minute or less, the authors draw the conclusion that where underground pipes or cable sheaths reverse more or less continually in polarity, the algebraic average of the current or potential is more nearly a correct index of the total damage that would result from electrolysis than any other figure that can be obtained. All of the tests described in the paper were however made with reversed currents whose algebraic average is zero. In order to prove the validity of the algebraic average for judging danger from electrolysis, it seems to me that it would be desirable to make experiments in which the algebraic average is other than zero, and particularly with reversed currents in which the periods for the positive lobes are made substantially longer than the periods for the negative lobes.

From a practical standpoint it seems to me that it would also be very misleading to give only the algebraic average of the potential or current, where these quantities continually reverse. This will readily be seen from the fact that large currents may reverse in underground cable sheaths or pipes, and yet the algebraic averages may be zero, so that if the results are expressed only as algebraic averages, an entirely false impression is created. There are other dangers from stray currents flowing on underground pipes and cable sheaths besides electrolysis, as for example fire hazards from sparks or arcing where currents pass through buildings on service pipes or cables. These dangers are not in any sense measured by the algebraic average of the currents.

I want to say in conclusion that if the low coefficients of corrosion found by the present authors, even with very slowly reversed currents, are substantiated for soils generally and for the low current densities usually met in practise, methods of electrolysis mitigation which result in large areas of reversing polarities of the underground structures, such as insulated return feeder systems and three-wire systems, assure a much greater degree of protection from destruction by electrolysis of these structures and particularly of iron structures, than has previously been expected. The work described by the present authors has therefore wide practical application and it is fortunate that we now have the results of this work available.

J. L. R. Hayden: I agree with the author's conclusions except in some minor features.

I do not believe that there is a limiting frequency beyond which no appreciable corrosion occurs. While at 25 cycles, the corrosion is already less than 1 per cent in most cases, there is still a distinct decrease at 60 cycles, and traces of electrolytic action seem to remain even at very much higher frequencies. At the low current densities used in the experiments the chemical corrosion is comparable with the electrolytic, and as the chemical corrosion is very variable, a serious source of error results at these frequencies, which in my opinion is the cause of the apparently negative corrosion at 60 cycles, in Table V.

I agree with the experience that alkaline solutions chemically protect iron, but attack lead.

The low coefficient of corrosion of lead may be apparent only, and due the assumption of lead as bivalent. As in the lead storage battery the anodic action proceeds to PbO_2, it appears probable that with unidirectional current of long duration, Pb shows valency 4. This would double all the corrosion coefficients of lead. At higher frequencies, lead probably is bivalent, and this would account for the different slopes of the lead and the iron curves.

The observer's results seem to agree with my experience that iron is more erratic than lead. This I explained by the ease, with which iron can assume the passive (probably trivalent) state. As time, current density (even momentary), previous history and nature of electrolyte (nitrates favorable, chlorides unfavorable for passivity) and surface condition (presence of scale) have a material influence on passivity,* during half cycles of long duration the iron electrodes may change from active to passive and inversely. As active iron appears to be bivalent, passive iron trivalent, the previous hydrogen electrode, when changing to anode by reversal of current, would tend to start active. This may account for some of the differences between the odd and even electrodes.

As nitrates and ammonia are frequent constituents of soil, and nitrates have a strong passivating effect, it would have been interesting to make some experiments with soil containing ammonium nitrate for instance.

Also, the action of higher current densities would be of interest, especially with lead electrodes. Lead cables laid in ducts are usually fairly well insulated except locally, where moisture may have penetrated etc. With such lead cables the current flow may be localized, and then higher densities result.

S. M. Kintner: The practical value of the information sought by the author, in so far as it relates to engineering practise in most instances at least, is the assistance it will give in forecasting what will happen to a pipe or lead covered cable buried in the ground and subjected to such electrolytic actions. A pipe, or cable, under such conditions fails by a small hole, or at least only a small hole is sufficient to cause serious trouble very shortly. This being the case it is of rather academic interest to know whether the pipe as a whole has lost one per cent in weight, or even ten per cent.

Even if we knew, quite accurately how the loss varied with current density etc., we could make no practical use of it, in an application such as that assumed, for the very evident reason that we have no control over the current distribution as it goes to or from such a buried pipe. What we are interested in, however, is the order of the loss that may be expected, compared to that due to d-c. electrolysis, or to ordinary corrosion under like conditions of soil.

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* "Electrolytic Corrosion of Iron by Direct Current", *Journal of Franklin Institute*, October 1911.

The paper contains some very interesting results on the effects of infrequent reversals of direct current. These results are of considerable practical value, if applied with proper discretion.

In a series of tests on a-c. electrolysis made by me in 1904-5 and reported in part in the *Electric Journal* of 1905, attempts were made to secure accurate data. Both iron and lead plates, weighed accurately before and after subjecting them to a-c. electrolytic action, were used.

The plates of iron in some test boxes, and lead in others, were arranged so as to form the two ends of small boxes, of which the other sides were of wood. Some 20 or 30 of these were used in various combinations of frequencies, of electrolytes, of current densities etc. It did not take long, however, to show that the current densities varied greatly, that the "gain" plates of the direct current cells lost as much, or more than those plates subjected to the simple corrosion or to the a-c. electrolytic action and that the cleaning for weighing was apt to produce greater losses than the losses it was expected to detect.

The d-c. "loss" plates would be eaten through at places slightly below the surface, while at other places down deeper in the solution the action was comparatively slight. This was quite conclusive proof that the current densities were not uniform over the whole plate surface. The mounting employed was expected to eliminate the greater density at the edges of the plates and thus secure a closer approximation to uniformity of current density.

It is to be noted that in the present paper no such precautions were taken and so it is reasonable to expect even a greater variation in current density than in the tests made by me in 1904.

After concluding a number of the plate tests, all laboratory tests, and reaching the decision that no data of a greater degree of refinement were obtainable or even if obtainable, could be applied practically, it was decided to check the general observations by tests approximating as nearly as possible, the actual operating conditions. Consequently a number of pipes of about four feet length and three inches in diameter, were buried after being carefully weighed, marked and having their ends sealed with an asphalt gum. These pipes, both commercial wrought pipe and lead cable, were buried in three different localities separated some 25 miles from each other. These test pipes were arranged in groups in each of the three localities and in this way the effects of frequency, current density, (insofar as total current per pipe would indicate it) direct current and simple corrosion were observed. Pipes were buried at different depths varying from two to six feet. There was a sufficient number of pipes in each combination to permit the removal of some after various periods of action. They were all removed at the end of one year.

Attempts at weighing and checking against the original weights, proved of no value whatever.

A careful study of them did show that effects of the a-c. electrolysis, both 25 and 60 cycle, was just about the same as that shown by pipes subjected to corrosion only.

Fortunately the character of soil, in the three places in which they were buried, differed very materially.

The effects on the pipes of the alternating currents followed quite closely, in each of the three places, that produced by corrosion only.

The serious effects noted were pits, some quite deep, while the pipe immediately adjacent was in good condition with no signs of pit marks. The pits were no different on the pipes subjected to the alternating current than those where corrosion only had caused the action. This indicates either a variation in the pipe, or a variation in the soil in which it is buried, which sets up a very strong local activity.

Carl Hering: The results given in the paper are of interest and of value, especially as some of them are different from what was probably supposed to be the case, while others confirm by experiment what heretofore was a mere belief. One of the most valuable results is that in what are called the neutral districts in underground electrolytic corrosion problems, the periodic reversals of current practically neutralize each other; also that corrosion from underground alternating currents of the usual frequencies, is not a serious menace; there were good reasons for believing that for lead covered cables at least, the corrosion due to underground alternating current might be serious.

Asa P. Way: This paper suggests an attempt made about six years ago for the mitigation of electrolysis in two instances, one of which was very familiar to me. In this method a specially designed transformer was used through the low voltage side of which passed the return current of one or more pipe drainage feeders connected to taps of different potential. The primary was excited through resistance by an intermittent current from a 550-volt d-c. source. The idea was to set up a relatively low frequency reversing potential between pipes and rails. However, financial as well as mechanical difficulties, I believe, prevented the development of the installations, although there appeared to be merit in the scheme.

However I have had in mind for some time to use the principles set forth in this paper in connection with the insulated negative feeder system but particularly with such an installation put in operation about two months ago. In this particular installation two of the feeders connect to a track about 4000 feet apart where tracks are consistently negative to water pipes although conditions are not dangerous, due principally to some poor track bonding in the neighborhood. My idea is to place in series with each of these feeders a definite amount of resistance alternately to be short circuited by automatically operated contactors. The resistances would be so designed that when one is short circuited and the other is in series with the other feeder and vice versa the potential between pipes and rails at the ends of the feeders would alternately reverse. It might be found that one resistance in series with the return current of both feeders could be alternately short circuited and left in series which would probably increase the area subject to reverse current flow between pipes and rails. The contactors could be operated by a relay controlled by a sign flasher or any other convenient method. I would like to know if the authors of this paper think that would be effective.

C. B. Martin: The tests described in this paper were made in soil. This condition is the usual one that must be considered in connection with standard trolley roads, but in connection with electrified heavy traction roads the effect of reversing currents upon steel imbedded in concrete becomes of importance.

For the last twenty-five months we have had under test, units made of one inch steel rods, six inches long, surrounded by two inches of concrete placed in water baths in metal pails. In some of these units the current has flowed in the direction to produce electrolysis of the rod, and in others the same current was reversed at the rate of 0.8 cycles per minute. The resistance of the d-c. units increased steadily, while that of the reversing units hardly at all.

How well the steel embedded in concrete of the d-c. unit automatically protected itself will be seen by the reduction of the current with the same impressed potential. At the start the current flow was 0.08 amperes; in ten days 0.04; in thirty-four days 0.02; in three hundred and twenty-eight days 0.01, and in seven hundred and sixty days 0.005. The efficiency of corrosion for the whole period was 28.4 per cent.

The average current flowing was 0.053 milliamperes per sq. cm. of the surface of the rod, which is about one-tenth of that required to produce the maximum corrosion of iron. This low density is, however, very much above that encountered upon the steel structures in which we are most interested.

An examination of the reversed current electrode showed that it was but slightly affected. Only 0.588 of a gram of metal had been removed, and the efficiency of corrosion was only 0.95 of one per cent of the positive current flowing.

The results of our reversing tests on steel in concrete, therefore agree very closely with the results reported in the paper on reversing tests in soil. In both cases the resulting electrolysis is practically negligible.

Another test which we made in 1912 is interesting. An electrolysis test sample similar to those described above which had been under test for three weeks with a positive potential on the electrode increasing from 12 volts to 52 volts, as the internal resistance of the sample increased, was subjected to a current reversing every minute, and the varying resistance of the circuit recorded.

See Fig. 1. It will be seen that very promptly upon the reversal of the current there was a surprising drop in the resistance, which was partially restored upon again making the electrode positive. Under repeated reversals the resistance of the sample steadily decreased with every indication that a stable condition had been reached. Finally the electrode was again subject to a steady positive potential and the resistance increased to an approximation of its original value. Naturally the question arises what caused the resistance to increase and decrease in this manner? Was the action due to gases or the expulsion and return of the electrolyte? At any rate the test shows that the resistance of the electrolytic circuit of steel encased in concrete is built up by making the steel positive, and broken down by making it negative.

Electrolysis engineers working to protect underground structures from electrolysis have constantly before them the statement that one d-c. ampere flowing steadily for a year will disintegrate twenty pounds of iron, or seventy-five pounds of lead under favorable conditions. Should such rates of deterioration be realized in practise many important structures would be in need of extended repairs, and the expenditure of very large sums in protective measures would be justified.

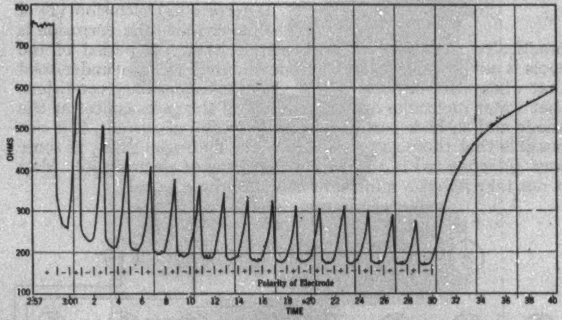


FIG. 1

When, however, foundations, especially steel foundations encased in concrete have been uncovered and found to be but slightly affected, although subjected to a potential favoring electrolysis for years, the question naturally arises whether there are not circumstances which in practise largely reduce these large estimates of electrolysis damage.

The paper of the evening demonstrates the existence of at least one very important condition that materially retards electrolysis in many localities.

An important conclusion that should be drawn from the paper is that in an electrolysis survey, readings should be taken for twenty-four hours, preferably by means of recording instruments so that the full cycle of a day's operations will be included and all current reversals recorded.

We are particularly interested in the statement that the loss of lead in soil under d-c. flow is about 25 per cent of the theoretical loss. We trust that this important phenomena will be more fully investigated and explained. Tests which we have made upon electrolysis samples of steel surrounded by two inches of concrete indicate that the efficiency of corrosion is not over 30 per cent. Some of these tests have extended over long periods.

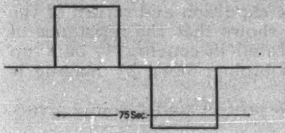


FIG. 2

Referring to conclusion (2) of the paper that "the corrosion is practically negligible for both metals when the period of the cycle is not greater than about one minute," we have understood that when electrolysis is taking place under ordinary conditions that water molecules are broken up and the gases collect at the anode and cathode surfaces. Upon reversal of current, is it not possible that these gases, especially the hydrogen gases, in some way interfere with the prompt starting of electrolysis? May it not take about a minute to dissipate these gases?

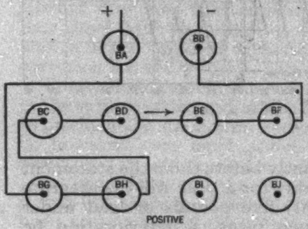


FIG. 3

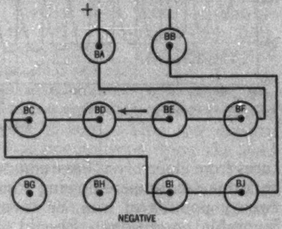
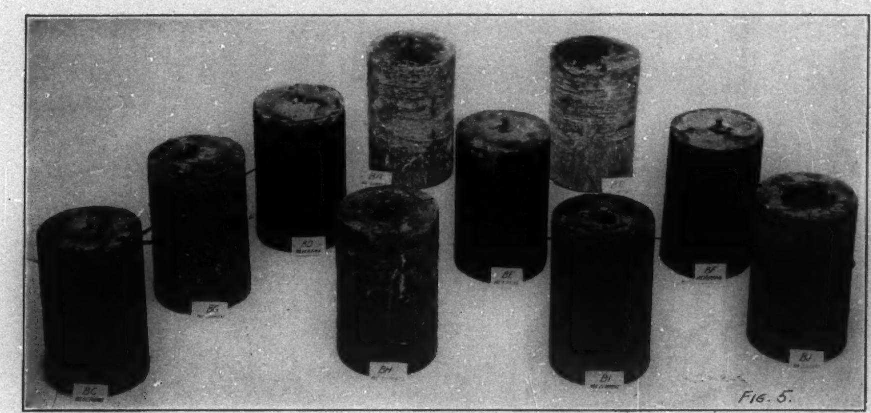


FIG. 4

In the twenty-five months' test referred to above, there was a period without flow of current between each reversal amounting to about one-third of the time. The shape of the current curve is shown in Fig. 2.

In addition to the four samples subjected to reversing test there were six others that were connected in circuit as shown in Fig. 3 and Fig. 4.

In Fig. 5 is shown all the samples at the end of the twenty-five months, each sample being lettered corresponding to its position in Fig. 3 and Fig. 4.


BC
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AD
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BH
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FIG. 5.

FIG. 5

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Thomas M. Roberts: My remarks will be a brief comment on conclusion No. 8.

Fig. 6 represents a rise of potential in a pipe line above a given zero, and a simultaneous drop of potential in the rails with the going and coming of cars. It is to be noted that the change of potential of the conductors in the earth is greater as the distance between the bond points increases. This probably is known to many railway engineers, but it is not so well known to many who install underground systems of piping which may become bonded with electrical conductors. I simply call attention to the fact that in an active zone a well bonded system of pipes and conductors suffers less from electrolysis than a poorly bonded system. This we know irrespective of whether the electrolytic effects are caused by an arithmetical average or by the algebraic sum of the currents. The effect is what it is, irrespective of the name given to the cause. The name is a small matter; the method of installation is the important thing.

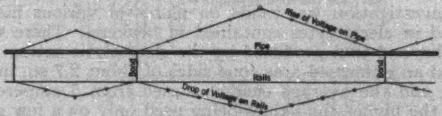

FIG. 6—DIAGRAM SHOWING INCREASE OF POTENTIAL DIFFERENCE BETWEEN PIPE AND RAILS WITH INCREASE OF DISTANCE BETWEEN BONDED POINTS

L. W. Chubb: We carried out about a year ago a test with slow reversal currents. In the control of large induction motors it has become quite common to feed the secondary through a water rheostat, as it is called. The frequency of alternation starts at 25 or 60 cycles, and as the motor speeds up the frequency drops to the slip frequency which is less than one cycle per second.

There has been some corrosion trouble with the metal electrodes in different parts of the country and very careful tests were made to find the effects of purity of water. These tests were carried out not in as much detail as they might have been, but they showed conclusively that the water, although reasonably pure, as pure as the moisture of the soil, has a great bearing on the result. Tests were made from 60 cycles down to 0.1 of a cycle per second, the low cycles being obtained by feeding from the secondary of the induction motor, with a constant slip, and by reversing direct-current with a rheostat which cut in and out the resistance, so that the wave shape approximated a sine wave. The specific results are covered in Mr. Spooner's discussion.

Sodium carbonate is used in water rheostats. It is used because it causes little corrosion. For this reason I believe it was not a very representative chemical to add to the soil employed in the test described in the paper. I think it is to be regretted that the authors cleaned their samples as they did, and did not take off the scale before the test was made.

Prof. Ganz said, that the usual current reversals do not have an average value of zero. I might say that it is possible that the average value of the test current was not zero in these tests, which may account for the great discrepancy between odd and even plates, and also increase the results. If the ampere-hours in each direction are equal, we should expect a very much lower corrosion than if there is, say, one per cent increase in one direction over the other. In our tests we met this trouble, and had to make a good many of the tests over again. We used ampere-hour meters to integrate the current first in one direction and then in another.

Thomas Spooner: Almost a year ago we made some tests on the effect of frequency of alternating current on the rate of corrosion of various metals and alloys in solutions of 2 per cent sodium carbonate and in sea water. The tests were largely qualitative, but they may add something of interest to this subject.

The investigation was made on plates of various materials immersed in electrolytes contained in beakers. There was no stirring beyond that produced by the electrolytic action. Each plate had an immersed area (one side) of about 2.7 sq. in. (17.4 sq. cm.) and the average current varied from 5 amperes to 1 ampere, the higher the values being used only on a few preliminary tests. The average current for most of the tests was about 2 amperes. The tests were made with various frequencies from 25 to 0.1 cycles per second. The results are expressed in loss of weight in grams per ampere-hour. Some of the results obtained are as follows:

TABLE I.—ELECTROLYTE—2 PER CENT SODIUM CARBONATE

LOSS IN GRAMS PER AMPERE HOUR

Frequency cycles per sec.	*Ingot iron	Monel metal	Nickel chromium alloy	Current supply
0.1	0.0175	0.0008	0.0021	Reversing switch
0.1	0.0155	0.0014	0.0030	Revolving rheostat
0.2	0.0055	0.00077	0.0030	"
0.5	0.0021	0.00084	0.0017	"
1.0	0.0011	0.00056	0.00078	A-c. generator
5.0	0.00015	0.00011	0.0022	"
25.0	0.000012			Shop supply

TABLE II. ELECTROLYTE—SEA WATER.

0.1	Badly corroded in 3½ hrs.	Badly corroded 3½ hrs.	Entirely eaten away in 1½ hrs.	Revolving rheostat
1.0	0.0041	0.0111	0.0498	A-c. gen.
5.0	0.0022	0.0098	0.0401	"

*Ingot iron was tested in sodium carbonate solution with d-c. It was badly corroded at end of 9½ hours.

A few tests were made on a 5 per cent nickel steel alloy (rolled), a 5 per cent nickel steel alloy (cast), and boiler plate. The first two corroded rapidly, while the last at frequencies of 0.5, 1.0 and 5.0 and a 2 per cent sodium carbonate solution gave the same results as the ingot iron within the limits of accuracy of the test.

The first 0.1 cycle tests were made with a motor driven reversing switch which was open about the same length of time it was closed. The revolving rheostat tests were made with an apparatus as shown in Fig. 7. The operation of the device is obvious from the figure. It gave a wave like that shown in Fig. 8.

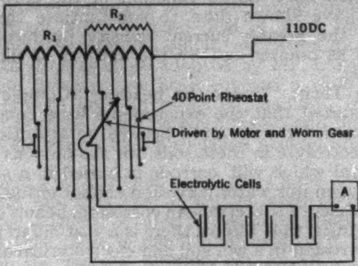

FIG. 7

The resistance R^2 (Fig. 7) was introduced to correct a slight dissymmetry in the positive and negative halves of the current wave. This device was substituted for the reversing switch because it was difficult to make the time of closure of the switch the same for both directions and because for this particular investigation it was desired to have the wave form approximately that of a sine. The average value of the current was determined by an integrating d-c. ammeter which was reversed each half cycle. The ratio between the maximum current and this average was calculated and considered constant for the several succeeding tests. The equality of the positive and negative halves of the current wave was checked by means of a copper voltammeter.

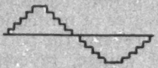

FIG. 8

These tests induced us to arrive at the following conclusions:

(a) The lower the frequency the greater the loss in weight of the electrodes, this loss increasing very rapidly below 0.5 cycles per second.

(b) All of the substances investigated corroded very rapidly with d-c. currents.

(c) Where considerable chlorides are present in the electrolyte, ingot iron seems to be superior to any of the other substances investigated.

(d) With low frequencies, monel metal seems to be the most satisfactory with 2 per cent sodium carbonate solution.

(e) Boiler iron seems to have almost the same loss as ingot iron.

(f) Very large differences in loss were obtained depending on the condition of the surface of the plates. This may account for the peculiar increase in loss for the nichrome at 5.0 cycles (see Table I) as this material is especially susceptible to surface conditions.

Some previous investigators have thought that the electrode loss per ampere hour was a function of the current density. Where they have shown data to substantiate this, is it not possible that the greater current density produced a stirring action, which as pointed out by the authors of this paper, increases the loss.

Maximilian Toch: Under the heading "Complete Series of Tests," it is stated that the experiments were conducted with iron and lead buried in soils, and I believe no attention has been paid to the electrolyte in these soils, for the obvious reason that if steel or metal which will corrode is buried in a soil in which there is no oxygen nor water corrosion cannot ensue, and I have seen so many cases of subterranean corrosion, beams of buildings, pipes and conduits, that I know there is a vast difference between electrolytic corrosion in a wet soil and electrolytical and chemical corrosion in a semi-dry soil.

In fact, I have gone so thoroughly into this subject that I am even now conducting experiments on the western coast of South America in a climate which I believe is much dryer than that of Arizona, and I have conducted experiments in the southern part of Nevada and the northern part of Arizona on the protection of steel against corrosion under various conditions. I say this in order to qualify before you, for I have paid a great deal of attention to this subject in the last twenty-one years.

Burton McCollum: Mr. Torchio has raised the question as to why the principles brought out in the paper have not been heretofore applied by electric railway interests for the mitigation of electrolysis troubles. The reason I think is quite apparent, namely, that in order to secure anything like the high degree of protection that would be desired it would be necessary to reverse the polarity of the trolley several times a day, although of course, reversing once every 24 hours would accomplish something. To reverse the polarity of the trolley once an hour or oftener would introduce an operating complication that few if any, railway men would consider. Such frequent reversal would be objectionable even where an entire system is supplied by a single station, and would be practically prohibitive in the case of a railway system fed by several interconnected stations. It is largely for this reason I think that the work of Mr. Larsen has not been given more attention. I would point out in this connection that the work described in the present paper covers an entirely different field and was undertaken for an entirely different purpose from the work done by Mr. Larsen. Mr. Larsen's object was to determine whether or not it would be feasible to reduce electrolysis trouble by a frequent reversal of the trolley polarity, and he carried out no experiments in which the current was reversed more frequently than once an hour. In the present investigation it was our aim to determine the order of magnitude of the corrosion that would be produced in the so-called neutral areas of railways where the reversal takes place at short intervals of from a few seconds to a few minutes. In order to make the investigation complete we carried out some experiments with alternating currents of ordinary frequency on which a good deal of work had previously been done, and also extended our investigation into the regions of long periods such as those adopted by Mr. Larsen. Between these extremes however, we have covered a wide range which has not heretofore been investigated, namely, frequencies of reversal such as those found between tracks and pipes and other underground structures in the so-called neutral areas of electric railways.

I wish to make it clear that the authors have not put forward this data with any idea that it will be used as the basis of a comprehensive system of electrolysis mitigation, and we do not consider that there is much likelihood of it being used in this way for the reasons pointed out above. Our principal purpose in bringing out the results of these tests is to show that in so-called neutral areas the actual amount of corrosion that will take place is much less than has often been supposed, and that the extension of the neutral areas due to the application of insulated return feeders, three-wire systems, and other methods of mitigating electrolysis troubles, need not be regarded as introducing any additional hazard to underground structures.

Regarding the criticism brought out by Prof. Ganz and Mr. Maxwell, I would say that the current density of 0.5 milliampere per sq. cm. was used for the reason that this is about the lowest value that is likely to be of any practical consequence. If the current density is 0.5 milliampere per sq. cm. the actual rate at which the iron would be corroded away would be approximately one centimeter in 12 years. This is a rate of corrosion which is frequently encountered in practise where electrolysis conditions are only moderately severe. Much higher current densities are frequently found, however. On the other hand, it is perfectly true, as Mr. Maxwell and Prof. Ganz have pointed out, that in practise, especially near the so-called neutral zones, the current density may often be but a very small fraction of that used in the tests, but it must be admitted that such current densities are of no practical importance. For instance, if we use a current density of 0.0046 milliampere per sq. cm., which Mr. Maxwell states has been actually found by him, it would appear that it would take about 1300 years to corrode the iron to a depth of one centimeter. While it may be true that the effect of reversed currents with these low current densities may be very different from that observed in these experiments, it is evident that the rate of corrosion in any case will be so low that it is of no concern from a practical standpoint, however interesting it might be from a purely scientific point of view. In this connection I would say that the corrosion on the test specimens used by the authors, while not strictly uniform, was nevertheless so well distributed over the surface that it was evident that the current density at any one point was not very greatly in excess of the average value of 0.5 milliamperes per sq. cm. used in these tests.

Prof. Ganz states that the tests were made in only one kind of soil. This is quite true. Part of the tests were made in the natural soil and some with sodium carbonate added, and the results, while slightly different, indicate the same general law. It is not improbable that with soil from different sources it would be found that the knee of the corrosion curve, or the point at which it begins to rise abruptly, would be shifted more or less. Nevertheless all of the experiments made indicate that the effects would be of the same general character as here observed.

Prof. Ganz quoted some figures from the table and seemed to convey the impression that they are misleading. For example, he stated that the table shows that with a ten minute reversal in the case of lead the coefficient of corrosion given is 0.132, and he appeared to assume that this is intended to show that the ratio of the corrosion on this frequency to the corrosion on direct current would be 0.132. This error might readily creep in provided the authors did not give the actual corrosion on direct current, but since this is given and shown to be approximately 0.25 I do not see how any one could be misled as to the magnitude of the reduction in corrosion produced by the reversals.

Prof. Ganz also suggested that in view of the fact that all of the experiments described in the paper were made with periodically reversed currents in which the algebraic average was zero, that it would be desirable to make additional experiments with unsymmetrical alternating currents in which the algebraic average is not zero. This I think is a good suggestion and I hope that it may be possible to make such experiments in the near future.

Mr. Way described a plan which he expects to try out whereby he hopes to utilize the principles set forth in the paper for reducing electrolysis troubles. If I understand his plan correctly, it would amount to superposing on a unidirectional current a symmetrical alternating current of sufficient magnitude to reverse periodically the polarity of the pipe. This would not have the effect of reducing the algebraic average of the current, so that if I have not misunderstood his plan I do not see how it would materially reduce electrolysis troubles.

Mr. Chubb suggests that possibly the positive and negative half waves were not equal and that this may in part account for the large discrepancy in some cases between the corrosion of the odd and even electrodes. This seems very unlikely since great care was taken to avoid any error of this sort. An oscillographic record carefully analyzed in a considerable number of cases did not reveal any appreciable unbalance.

I have been particularly interested in the results presented by Mr. Spooner as they were made under different conditions using a liquid electrolyte instead of soil, but nevertheless the results obtained on ingot iron are substantially in accord with the results presented in our paper.

Presented at the 320th meeting of the American Institute of Electrical Engineers, New York, April 14, 1916.

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HIGH-VOLTAGE D-C. RAILWAY PRACTISE

BY CLARENCE RENSHAW

ABSTRACT OF PAPER

During the past 10 years, the operation of electric railways at d-c. voltages of 1200 and 1500 has become common and higher voltages have been shown to be practicable. The paper deals first with the fundamental differences in apparatus for 1200 or 1500 volts as compared with the former 600-volt standards and indicates the apparent tendency of general practise with regard to a number of alternative constructions which must usually be considered in each specific application of these systems.

Referring then to the use of higher d-c. voltages which is just beginning, it points out the tendency to reach an ultimate maximum by employing a multiplicity of voltages differing but slightly from each other, such as 2400, 3000, 3600, 4200, etc, for successive installations. It recommends, in order to avoid the confusion which must surely result from this, that efforts be made to establish at once a single standard for high-voltage lines.

The paper shows that final standards in voltage are usually fixed by broad economic considerations rather than by physical limitations and suggests that 5000 volts direct current would offer a very satisfactory voltage for such a standard if commercial apparatus for this voltage were available. Finally, it touches briefly upon the operation of the experimental 5000-volt line at Jackson, Michigan, which has been so successful as to give great hope that the system will be commercially developed.

TEN YEARS ago, the idea that approximately 600 volts was the maximum potential to be hoped for in the operation of d-c. railways was almost as firmly established as was the belief in the days of Columbus that the earth was flat. On a few roads, it is true, 650 or even 700 volts was carried at the station and in an occasional rare instance, the use of a booster gave a maximum of 800 or 900 volts. Drop in the feeders, however, usually reduced these values considerably before they reached the car, so that these instances represented merely the generation of d-c. power at voltages above the nominal 600 rather than its utilization by the car motors.

Then suddenly the plan was suggested of coupling the four 600-volt motors ordinarily employed on interurban cars in pairs of two in series instead of two in parallel, and of connecting the generators in the stations in a similar manner, so as to employ

1200 instead of 600 volts. Two railways then under construction were willing to try the scheme, and although there were some misgivings as to whether it would work or not, it did. The entire railway industry as a result has been given a lesson in open-mindedness which it should not soon forget and the use of d-c. voltages of from 1200 to 1500 for the operation of interurban railways has become so common that today we are able to discuss details of high-voltage d-c. practise.

MOTORS

Limiting ourselves for the time being to voltages of 1200 and 1500 in discussing the matter, the first element to be considered of a high-voltage car or locomotive equipment is of course the motor. As far as voltage between terminals is concerned, the requirements for motors to operate two in series on such voltages differ from those for low-voltage service only in the fact that slipping of the wheels to which one of the two motors in series is connected may interfere with the normal voltage distribution between them, and concentrate a large part of the total voltage at the terminals of one machine. Fear of this contingency at first led to the design of motors for high-voltage service with a much larger number of commutator bars than for corresponding 600-volt service. More extended experience, however, showed that such precautions were unnecessary.

Insulation and creeping distances on motors for high-voltage service must of course be made suitable for the full potential. This was accomplished at first by " main strength and awkwardness," as it were, and the limitations imposed by the extra insulation, extra creeping distances and extra commutator bars ordinarily carried with them a considerable sacrifice in capacity when a given motor was wound for operating two in series on 1200 volts instead of two in parallel on 600. As in the matter of commutator bars, however, wider experience gradually overcame this difficulty. The extra insulation required for 1200-volt operation is now obtained by the use of better quality rather than greater quantity of material, and the extra distances by improved shaping and arrangement of parts. Generally speaking, therefore, motors are produced today for use in series on 1200 or 1500 volts with the same dimensions and weights as if made for use on only 600 or 750 volts.

In referring to motors above, I have spoken as if the coupling of two 600- or 750-volt motors in series was the only arrangement ever employed for utilizing 1200 or 1500 volts. There have been, however, one or two instances where motors have been wound directly for the full line potential. Speaking generally, such motors are heavier and depart more radically from standard low-voltage designs than motors for operating two in series, and moreover, they do not lend themselves as well to the operation of the cars partly on 600 and partly on 1200 volts, which is so often required. In general, therefore, they seem to offer no particular advantages and are hence but little employed.

High-voltage d-c. railway practise, therefore, in the matter of motors may be said to consist in the use of two machines in series, these being identical in construction with standard motors for low-voltage service except in the comparatively minor details of quality of insulation and length of creeping distances.

CONTROL

In control apparatus for high-voltage d-c. railway equipments, the fundamental requirements are to provide sufficient circuit-opening capacity to overcome the greater tendency to "hang" which the high-voltage arcs possess, together with the necessary means to confine these arcs within proper bounds.

The first result was secured in the early high-voltage apparatus by using two 600-volt switches in series at practically every circuit-opening point, and the second by liberal increases in the insulation and space surrounding all live parts. Thus our first 1200- and 1500-volt car equipments employed 13 pneumatically-operated switches, where with the same current at 600 volts eight would have been sufficient. The groups in which these switches were assembled, also, were approximately 24 in. (60.9 cm.) wide and 24 in. deep as compared with 18 in. (45.7 cm.) wide and 22 in. (55.8 cm.) deep for the corresponding 600-volt apparatus.

As with the motors, however, greater experience led to a reduction of these differences in the fundamental parts. Some of the extra switches in the first equipments came into play only when the controller was "backed off" from parallel to series, and by improvements in interlocking the work of opening the circuit at this time was transferred to another point so that these extra switches could be omitted. Another switch had been employed because it was feared that the high-voltage motors might require more careful handling and hence more resistance notches than standard 600-volt motors. It was found later that such was not the case and this switch also was omitted in future equipments. In these ways, in the types of equipment most generally employed, the additional switches necessary on account of the increased voltage have now been cut down to two for small equipments or three for large ones. In dimensions also, it has been possible to work out designs for 1200-volt switch groups with the same cross-sectional area and the same weight per switch as those for 600 volts.

Auxiliary Control Devices. The introduction of the new element of operating at double voltage has greatly increased the number of possible combinations and alternatives which must be considered in any given case in order that they may be adopted or rejected.

In the first equipments for use on 1200 volts, it was considered undesirable to attempt to employ this voltage for the auxiliary circuits such as lights, control, air compressor, etc., and so a dynamotor was included as a part of the equipment to provide a supply of 600-volt current for such purposes. To reduce the capacity required of the dynamotor, the air-compressor motor was next wound for operating at full line potential, so that only the lighting and control circuits need be supplied at 600 volts. Even on this basis, the presence of the dynamotor in addition to the air compressor seemed unnecessarily burdensome, so that the next step was to combine the two machines in a dynamotor compressor. In this device, the air compressor, instead of being driven by a separate motor, as previously, is connected to or disconnected from the dynamotor when required by a suitable clutch controlled by the pressure governor. In locomotives or other equipments where forced ventilation is required, the operation is still further consolidated by mounting the blower fan on the shaft of the dynamotor so that the same machine in such cases serves a triple purpose. This offers considerable advantage in simplifying equipments, and the scheme of driving the compressor and providing 600-volt current for the auxiliary circuits from the same machine has become firmly established in high-voltage practise.

Where equipments are to be mounted on cars of small or moderate size, however, even this arrangement is somewhat of a handicap in the matter of cost and simplicity when comparison is made with the usual 600-volt equipment of the same capacity, so the next step was to arrange the lighting and control circuits for operation directly from the line voltage. With electropneumatically-operated control, this was readily done and on such a basis, 1200- or 1500-volt equipments have been made practically as simple, reliable and easy to maintain as those for operation on 600 volts.

As the art now stands, these two general arrangements for handling the auxiliary circuits constitute a dual standard and one of the first decisions to be made in planning any given installation is between these two schemes.

Operation on Two Voltages. The most prolific source of vexatious problems is the use of equipments part of the time on low voltage and part of the time on high. As far as the main-circuit apparatus is concerned, any high-voltage equipment will of course run on half voltage with a corresponding reduction in speed. In order that such operation may be satisfactory, however, special arrangements must be made to care for the auxiliary circuits.

Many interurban lines operate at high speeds over their own rights-of-way in the open country but enter one or more towns over the tracks of local 600-volt systems. High speed in the city is not permissible in any case and so approximately half of the normal speed when running on 600 volts is sufficient. For cars operating under such circumstances, it is common to provide for reconnecting the lighting and control circuits so that these will receive full voltage when the car is in the 600-volt section but so that the main motors will remain permanently coupled in series and thus operate at half speed.

If a dynamotor compressor is employed on cars which operate in this way, the same changes which are necessary in any case to care for the lighting and control circuits automatically care for the air compressor as well, connecting this for full speed on both voltages. In cases where approximately half speed on low voltage is sufficient for the main motors, however, the distances are usually short and half speed of the air compressor also is sufficient. Where cars which operate in this way employ a high-voltage compressor instead of a dynamotor compressor, therefore, no change is ordinarily necessary in its circuits for the low-voltage operation.

Since the motors on high-voltage cars are in general wound for only 600 or 750 volts each, the car can if desired be arranged to operate at full speed on both high and low voltage. Where this is required, a main change-over switch is employed which connects the motors of each pair either in series for high voltage or in parallel for low voltage, and which connects the two halves of each step of the main resistance in a corresponding way. Suitable connections for air compressor, lights and control circuits can also be included in the same switch so that the setting of a single piece of apparatus into one or the other of two positions changes the car at once for use on high voltage or on low voltage.

When the proper scheme of operation on the two voltages has been decided, the next point to determine is the manner in which the change-over should be effected. The simplest method in either case of course is the use of a manually-operated switch on each car. It is sometimes desirable, however, to have the change-over switch located beneath the car and arranged for operation from the platform. In other cases, it is desirable to have the switches arranged not only for distant control in this way but also for simultaneous operation throughout a train of cars.

To supplement the apparatus for changing connections on equipments so that they may be operated on either high or low voltage, protective devices are sometimes desired to prevent or minimize the trouble which may occur in case a car is subjected to high-voltage when its change-over switch is arranged in the low-voltage position. Such devices ordinarily consist of relays of some form which are so connected, when the change-over switch is in the low-voltage position, that they act quickly in case a voltage in excess of the normal is applied to the car, and cut off the circuits which are likely to be damaged.

The choice between automatic and non-automatic acceleration is not influenced particularly by the use of high voltages except that such voltages are more often employed for interurban lines where non-automatic acceleration is ordinarily considered preferable. The necessity for running on both 600 and 1200 volts in many cases also usually introduces certain complications in high-voltage equipments and there is a tendency to adhere to non-automatic control so that the simplicity of this will, as far as possible, offset the various complications which must be retained.

The use of field control or non-field control also is not particularly affected by the employment of high voltages except as influenced by the same general idea mentioned above with regard to the choice in the type of acceleration. For the sake of simplicity, there is a tendency to adhere to non-field control to offset unavoidable complications at other points.

Alternatives in Control Apparatus. It will be seen from the above that even with common practise in high-voltage equipment fairly well standardized, a host of alternatives usually present themselves for settlement in almost every case. The most common questions are—should the voltage be 1200 or 1500; should the equipment be of the dynamotor compressor or of the non-dynamotor type; will it have to operate on high voltage only or on both high and low voltage; if required to operate on low voltage as well as high, will half speed be sufficient on main and compressor motors or will full speed on both voltages be necessary; must the change-over switch be arranged for indirect control or will manual operation be sufficient; if indirect control is required, can it be confined to the individual cars or will simultaneous operation throughout the train be required; is a protective device essential to guard against damage by the application of the wrong voltage or will this not be required? Other similar questions might be added to the list but these are the most important ones.

Most of these matters are largely influenced by the individuals who control the local situation, so that it is difficult to generalize with any degree of accuracy. As far as I can judge, however, current practise seems to be tending in the following directions.

Where the high-voltage cars must run over existing 600-volt lines to any considerable extent, the exact ratio between 600 and 1200 volts offers some advantages. Since high-voltage motors are made from existing standards also, there is a wider range of choice for 1200-volt operation than there is for 1500 volts, especially where small sizes of motors are required. So far, 1500 volts has been used in sections where 600-volt lines have been established only to a limited extent, that is, in comparatively virgin territory, while 1200 volts has been employed in sections where there has already been considerable 600-volt development. It seems probable that high-voltage practise will continue to follow these lines except in the case of the electrification of branch lines on steam railroads or similar instances where connections with existing lines will have little bearing.

Speaking broadly, the general tendency is toward the use of the dynamotor compressor on large expensive cars, particularly where full speed is required on half voltage, since this arrangement lends itself readily to such operation. Dynamotor compressors also are particularly suitable for locomotives where forced ventilation is utilized. For smaller and less expensive rolling stock, non-dynamotor outfits are generally employed, although there is and always will be a certain amount of overlapping.

In the older sections of the country where distances of four or five miles must sometimes be run on city tracks, and where through cars over 600-volt lines are likely to be employed, equipments are usually required to operate at full speed on half voltage. Equipments for operating at half speed under these circumstances, however, offer considerable advantage in weight, cost and general simplicity and will undoubtedly find a considerable field where circumstances are favorable to their use.

Where large cars are arranged for full speed on both voltages, the tendency is toward the use of full speed for the air compressor also. On smaller cars where as a rule the compressor has more margin, half speed of this device is ordinarily thought sufficient even where the main motors operate at full speed.

In the matter of change-over switches, the general tendency is to employ the simple manually-operated type except where cars are operated at close headway or are constantly used in trains. In most cases, also devices to protect against the wrong voltage are not considered necessary.

Equipments with Drum Control. I have spoken in all of the above with particular reference to equipments using indirect or multiple unit types of control and primarily with reference to those using electropneumatic control. While high-voltage equipments are occasionally used with drum-type controllers, especially double equipments with rheostatic control where cars for city service are operated in small towns by interurban companies, the number of these is too small to warrant inclusion in any generalization such as that with which we have been dealing.

POWER SUPPLY

Direct-current power for high-voltage lines was first obtained by the use of two 600-volt generators, either engine- or motor-driven, connected in series. Since there was no particular object in retaining two generators in series such as there was for retaining two motors in series on the cars, generators for delivering 1200 or 1500 volts directly were soon produced. At first these were of the ordinary commutating-pole type. Such machines now, however, usually employ a compensating winding as well as commutating poles.

The next step in the production of high-voltage d-c. power was the use of two 600-volt, 25-cycle synchronous converters connected in series, and while this was considered a radical step at the time it was first proposed, the performance obtained was so satisfactory that single 25-cycle converters producing 1200 or 1500 volts on one commutator have now been developed and are in successful use. With 60 cycles, the maximum voltage so far employed from a single machine is 750 so that two machines in series are still required for high-voltage lines. The performance on this basis, however, is most excellent.

Common substation practise for high-voltage d-c. lines is now to employ single synchronous converters where power at 25-cycles is available, and to use either motor-generator sets or two converters in series, where 60-cycle power is employed. A particularly efficient substation arrangement on the latter basis is secured by installing three synchronous converters so arranged that any two of them may be connected in series. This gives a spare machine at a minimum expense. If a single bank of three transformers is used for supplying these converters, a spare transformer as well as a spare converter is also secured, so that the station is prepared for almost any emergency.

SWITCHING

In the matter of switching, the principal changes which have been made in handling current at 1200 or 1500 volts instead of at 600 volts have been for the purpose of insuring safety to the operators rather than for any other reasons. For this purpose, switchboard panels have been made higher than for 600-volt service and the circuit breakers located on them so as to be out of direct reach. For opening and closing the breakers, long wooden rods leading to insulated handles on the lower part of the panel, are provided. Where two or more breakers are located side by side, large barriers are placed between them to prevent any tendency to flash across. Knife switches have also been located out of reach in a manner similar to the circuit breakers and arranged with rods for distant control.

LINE CONSTRUCTION

The first 1200-volt lines employed direct-suspension overhead trolley with a special form of porcelain insulators. The catenary form of construction offers so many advantages for such lines, however, that generally speaking, the most common practise is now to employ this. Several interurban lines are using 1200-volt third rail successfully for supplying power but the voltage surges to which this may give rise under certain circumstances, the difficulty of clearing a car in case of accident and the general safety hazard incident to the maintenance of a live conductor so close to the ground seem likely to limit the use of this form of construction.

A growing practise on high-voltage systems is that of carrying the feeders for a considerable distance from the station before tapping in to the trolley so as to limit the possible current flow in case of trouble of any kind on the cars. With the excellent voltage conditions which can so easily be secured on high-voltage lines, the slight sacrifice which need be made for the sake of protecting the substation apparatus in this way can usually be well afforded.

ECONOMIC SIGNIFICANCE

In studying the development of 1200- and 1500-volt practise, the fundamental point which appeals to me is the ease, success and speed with which so radical a departure from previous practise has been carried out. In most developments of so far-reaching a nature, many sources of difficulty are usually overlooked at first and must be cared for in later apparatus at increased expense. In the high-voltage d-c. railway system, however, just the opposite has apparently happened. Many of the possible difficulties seem to have been over-estimated in importance and much of the trouble anticipated has failed to appear. It has therefore been possible to gradually simplify and cheapen the various fundamental parts which go to make up the system instead of having to follow the opposite and more usual procedure.

It is difficult to say whether this exceedingly gratifying condition was due to the more advanced engineering ability of the times, to the inherent simplicity of the d-c. railway apparatus, to the very excellent state which such apparatus for 600-volts had reached before its extension to higher voltages was attempted, or to the fact that the jump to 1200 or 1500 volts, while seemingly radical, really subjected the apparatus to conditions differing comparatively little from those met with in 600-volt practise. Whatever the cause may have been, however, the result remains as a remarkable tribute to those who shared in its accomplishment.

The general results of the high-voltage d-c. system have been to make possible the construction of interurban lines or the electrification of branch steam railroad lines at considerably less expense for a given grade of construction than with 600 volts, or to render possible for a given expenditure the construction of lines capable of handling much heavier traffic. The usual practise has apparently been a compromise between these two possibilities, which has served to finally transfer the electric line from the street car to the real railroad class as far as transportation possibilities are concerned, while still maintaining the relationship and similarity with reference to the simplicity and reliability of the apparatus. With practically no greater expenditure for substations and feeders than the usual 600-volt trolley line, such roads are able to employ freight or passenger trains after the manner of steam lines in accordance with the needs of their business instead of having to restrict them on account of limitations in the distribution of power.

2400 AND 3000 VOLTS

The comparative ease with which the use of 1200- and 1500-volt direct current was transferred from the realms of uncertainty to the list of every-day standards soon suggested the employment of still higher voltages. Inasmuch as the 1200-volt system had been brought about by the use of two 600-volt motors in series and as a few motors wound directly for this voltage had been produced with no particular difficulty, the obvious procedure was to continue the geometric progression and connect 1200-volt motors and generators in series so as to operate at 2400 volts.

From a technical standpoint, there was apparently no particular difficulty in doing this, and one line installed on this basis has had a remarkably successful record. From a general standpoint, however, while the results have been welcome as a contribution to the development of the art, suitable applications for this particular voltage are apparently somewhat lacking. For trolley roads of the usual interurban class, it has the inherent disadvantage of requiring apparatus which departs too widely from the existing standards with which the operating forces have become familiar, as well as of not lending itself to interchangeable operation over 600-volt lines. For heavy traction, on the other hand, this voltage is much too low to solve the problem in a sufficiently comprehensive way to attract the investment of capital in electrification. Even 3000 volts, while overcoming the latter disadvantage to some extent, does not do so completely. It is regrettable also that *both* 2400 and 3000 volts have been employed and that in carrying on the upward progress in d-c. voltages, 1500-volt apparatus was not used at once for coupling in series, for carrying on the geometric progression, without the intermediate 2400-volt step.

ULTIMATE LIMITS OF D-C. VOLTAGE

The general limits upon which standard practise in any industry ordinarily settles are usually fixed by broad economic considerations rather than by physical limitations. It is entirely possible for instance to operate trains at maximum speeds of 90 miles per hour or more, yet the maximum ordinarily attained is from 60 to 80 miles per hour. Physically speaking, also, interurban cars can be run at speeds similar to these, yet the general average on such roads is from 50 to 60 miles per hour. These values have been established by gradual increases from lower ones until without any conscious effort, standardization has been automatically secured.

In the voltages which may be employed with the d-c. railway system, there is some tendency toward this same procedure. If no efforts were made to the contrary, it is not improbable that starting from the voltage of 3000, which we have today on the Chicago, Milwaukee & St. Paul, we would next hear of the employment of 3600 volts, then possibly 4200 volts and so on up in corresponding steps. Sooner or later, however, a point would be reached where, by common consent, these increases would stop, just as this has happened in the matter of speed.

While in a way, such a procedure would be the conservative and natural way for progress to come about in the use of higher d-c. voltages, its disadvantages are too obvious to require mention. The apparently more radical plan of trying to select in advance the voltage at which such increases would naturally stop and of going at once to this voltage would hence seem to be the more rational and really the more conservative as far as the general good of the industry is concerned. It has been with this idea in view that our efforts toward the use of direct current at 5000 volts are being put forth. With practical apparatus for this voltage available, the problems of distributing and collecting the necessary power for the largest locomotives likely to be required can be readily solved so that although further increases might be possible, they should be entirely unnecessary.

OPERATION OF 5000-VOLT EQUIPMENT

The general construction of the 5000-volt experimental equipment on the Grass Lake line of the Michigan United Traction Co. and the results of its first few months' operation have been so widely covered by the technical press that it is unnecessary to refer further to them except to say that the equipment is still in operation on the same successful basis, and that at the time this is written, it has run a little over 30,000 miles. During the five months from October 1st to March 1st, the car averaged 5295 miles per month on a schedule which allows only 15 miles per hour and its record would have been even greater than this had it not been for numerous mechanical difficulties with the trucks, wheels, brake rigging, stove, pilots and other mechanical parts of the car for which the equipment was in no way responsible. During the four months of November, December, January and February, which, on account of weather conditions, are ordinarily considered the worst in the year, the car ran 23,320 miles or an average of 5830 per month.

During this period the car operated through severe snow, sleet and rain storms and for a short period even ran with two of the commutator covers missing, these having been lost on the road. The motors and control were purposely allowed to go with a minimum of cleaning and other care, and various reports sent in by the men in charge refer to the presence of wheel wash, dirt and other obnoxious substances in the motors and switch groups, although no damage was caused by them.

A half-dozen or so failures have occurred during the winter but these have been mostly in the nature of broken motor leads or similar troubles which served merely to test the practicability of the use of such a voltage under the general rough conditions to which car equipments are subjected rather than to indicate any inherent weakness. These troubles showed that this equipment could as easily withstand such ordinary mishaps as any equipment for 600 volts. Only two of the failures were in any way due to the use of 5000 volts and these consisted of grounds on the grid resistance which took place through the water-soaked flame-proof covering on certain of the leads where the cables had not been properly insulated and supported. Such troubles can be easily guarded against on new equipments.

While as yet only the one equipment now in experimental operation has been built, various designs of other sizes have been considered and with the special double-armature type of motor and double-jaw type of switch which have made this equipment possible, unusual flexibility in meeting a wide range of conditions can apparently be obtained.

In most of the considerations of the use of d-c. voltages of 2400 and 3000, there has always been a certain minimum size of motor which could be economically produced and this size has been undesirably large for certain classes of service. With the special double-armature type of motor for 5000-volt equipments, however, the experimental equipment already in use is about as small as would ordinarily be required, although even this is apparently not the minimum limit. On the other hand, the design seems equally adaptable to large sizes.

CONCLUSION

Broadly viewing the high-voltage d-c. practise which we find today, and its significance to the industry, there are four ideas which appeal particularly to me. The pernicious flexibility of the 1200- and 1500-volt systems and the innumerable alternatives which they present for application to any definite case in interurban work, seem to give timely warning of the great desirability of early standardization in the matter of higher d-c. voltages. The comparative ease with which apparatus for these voltages has been developed gives a most encouraging feeling for further development along the same lines. The possibilities which a d-c. system at 5000 volts would offer were the apparatus commercially available make this voltage seem a logical one and the results obtained with the experimental equipment now in operation give great hope that this voltage may some day be established commercially as a standard of high-voltage d-c. railway practise.

Discussion on "High-Voltage D-C. Railway Practise (Renshaw), New York, April 14, 1916

Frank J. Sprague:* Mr. Renshaw states that ten years ago the idea of approximately 600 volts as the maximum potential to be hoped for in d-c. railway operation was firmly established. I can claim that some engineers at least were not deluded with this conviction.

In the early days of stationary motor development I had built some special machines to operate normally at from 500 to 600 volts but which in the exigencies of service had been boosted to about 1000 volts; and on the 34th Street branch of the Manhattan Elevated in the latter half of 1886, where a number of the primary features of the modern electric railway were tried out, I operated at 600 volts from a third rail.

When, a year later, I took the contract for the pioneer trolley roads at Richmond and St. Joseph, I adopted a somewhat lower potential, 450 to 500 volts, which pressure and system were, however, even then regarded as extreme. This standard was gradually raised, however, to about 600 volts, and remained there for practically twenty years.

In February, 1890, at the Kansas City Electric Light Convention I stated, as follows:

> "As regards the potential, other things being satisfactory, whatever pressure is demanded in the interests of economical and effective service will be used; and means will be found, consisting mainly in care of construction, which will make its use for the purpose, and as intended, safe and proper. We have in these matters to face the same questions as we have in the matter of steam pressure or of railway speed. To accomplish the larger engineering feats necessary to meet the demands of economy and commerce we will be governed more by the belief in our power to fully subordinate a good servant to our will than by our fears of its vagaries when allowed to become a master."

In my inaugural address as President of this Institute at the Chicago Meeting, June 18, 1892, I pointed out that we were at that time, if using d-c. motors, practically limited to a difference of potential of from 1000 to 1200 volts, and that to go above that limit it would probably be necessary to put motors in series as I had sometime before proposed for long distance power transmission.

In March of 1904, in an article in the *Electric World and Engineer*, I said:

> "While d-c. motors may always be somewhat at a disadvantage in the matter of individual potential, when there is a plurality of motors, as in the large locomotive, it is quite possible on a d-c. system to work up to 1700 or even 2000 volts on a single trolley line, maintaining a maximum as in regular use on the Berlin Elevated, of from 850 to 1000 volts on individual motors; and if a three-wire system be used it is quite possible to make use of a maximum trolley potential of nearly 4000 volts."

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*Abstract of discussion published in August, 1916, Proceedings.

On the introduction of the interpole in stationary motor construction, I recognized the benefits of this construction for railway motors and advocated its adoption, pointing out that it would make possible an immediate increase in potential for direct-current railway work from 1200 to 2400 volts, without question.

In 1906 I urged upon the engineers of the Washington, Baltimore and Annapolis line the adoption of 1200-volt d-c. operation, and in the fall of the same year, I recommended to the consulting engineer of the Central California Traction Company the use of a 1200-volt d-c. third rail. My recommendation was adopted and the installation, the first of the kind, went ahead on this basis.

A month later I discussed quite fully the details of the 1200-volt operation with the consulting engineer of the Southern Pacific Railway Company, and recommended this potential for the Oakland suburban lines of the Southern Pacific system.

In a discussion before the American Institute of Civil Engineers in Nov., 1906, I called attention to the fact that, comparing the condition of the art then and a couple of years earlier, three important and radical developments had taken place in d-c. motor construction, the first of which was the use of the commutating poles, which, with additional facilities in control, made perfectly possible the construction of d-c. motors at from 1200 to 1500 volts, with the further possibility of operating two in series at double potential.

The remarkable departure in the construction of the New York Central gearless locomotives, in which the hitherto invariable practise of maintaining the fixity of relation between the armature and the field magnet has been abandoned, gave me occasion to point out that this machine was a natural 1200-volt machine without commutating poles.

In 1906, after a personal inspection of the Sacramento Division of the Southern Pacific Railroad, I recommended an electrical equipment operated with an initial potential of 1500 volts at the substation third-rail junction, and described the possibilities of electrical braking, both direct and regenerative, through the use of independently excited fields as now used on the Chicago, Milwaukee and St. Paul equipment.

In my early experiments on the Manhattan Elevated in 1886, I used, for the field as well as armature, rheostatic control for speed variations. I described a plan of regenerative as well as direct electrical braking before the Boston Society of Arts in 1885.

In the *London Times and Engineering Supplement* of April 10th, 1907, Mr. H. M. Hobart made a curiously exact prophecy, as follows:

> "My opinion is that within ten years, continuous-current systems as applied to railway electrification will employ line pressure more of the nature of 2000 or 3000 volts, and these systems will, in all probability, have come into extended use."

This is the year 1916. For practically twenty years the potential for d-c. railways remained unchanged at 600 volts. In ten years it has jumped to 3000 volts on the Chicago, Milwaukee and St. Paul Railway, one of the typically most difficult, and embracing in its 437 miles of line more route mileage than all the trunk line electrifications in the world. The 11,000-volt 15-cycle system is non-existent in this country, and not a new single-phase railway motor is now installed here except on the few systems remaining.

William J. Davis, Jr.: I do not think the Southern Pacific electrification presents any new problems at all. The discussion to-night seems to be along the lines of increases in voltage far beyond those used on the Southern Pacific. The Southern Pacific electrification has been in operation about seven years, and the success of the installation has been very marked.

As regards the tendency to higher voltages, it would appear that the proper voltage to be chosen for a given installation would depend upon the maximum tonnage to be hauled and limitations as to speed. The tonnage capacity of a system is dependent, we may say, upon the number of tracks that are in service. In a single-track road, if heavy tonnages are to be handled, it will be necessary to adopt higher voltages than would be necessary for a road having sufficient traffic to require two or three or possibly four tracks. In the case of a four-track road, all the tracks being in multiple, the drop in voltage in the track is greatly reduced, and we also obtain the advantage of the copper trolley wire or third rail for all four tracks in multiple, so that even when locomotives of very large powers are used, say 3000 or 4000 horse power it will be found in so far as the distribution system is concerned, that a moderate voltage, possibly 1200 or 1500, would prove as effective in handling the traffic as would 3000 volts, or more, in the case of a single-track or double-track road.

In a reduced number of tracks, some economy is gained in going to higher voltages, but the exact and most desirable voltage would depend not only on the saving in the amount of copper, but also on the load factor on the substations and the cost and number of locomotives required to handle the traffic.

In a single-track freight road, it will be found that upon the basis of the weight of trains now in use, very little improvement in load factor is secured if the substations are placed more than thirty or thirty-five miles apart. With this spacing, the copper required for delivering 3000 or 4000 horse power to a train is not at all excessive at 3000 volts, and is fixed almost as much by mechanical reasons and current carrying capacity as by the desire to secure a low drop in voltage.

Substation capacity also as applying to the whole system is not materially reduced, for the reason that the synchronous converters and motor generator sets are usually designed to stand three times normal load for a short time, and so long as at least 33 per cent load-factor is secured there will be no saving in the total amount of substation apparatus.

The whole problem, therefore, appears to be narrowed down to the question as to the number of locomotives required on a given division and their cost. As a general rule, the cost of the locomotives required for handling the traffic of a single-track road will amount to about one-third of the total cost of the electrification. If, therefore, there is a material increase in the cost of a 5000-volt locomotive as compared with one for 3000 volts, this increase in cost may prove the determining factor. In the case of the Milwaukee electrification, forty-two locomotives were required, and an increase in their cost of fifteen per cent, due to an increase in voltage, would exceed the total cost of feeder copper for the entire system as required for 3000 volts. In the case of a double-track road in which the locomotives would be greatly increased in number, this difference would be still more marked, and would point to limitations of voltage possibly not exceeding 3000 volts as applying to most of the heavy freight traffic now obtaining on trunk line railroads.

William B. Potter: It is a pleasure to endorse much of what Mr. Renshaw has said as to the excellent features of high-voltage direct current. We are, however, rather more concerned with the future than with the past, and I think that the text of the ultimate is very well covered in his statement that: "The general limits upon which standard practise in any industry ordinarily settles are usually fixed by broad economic considerations rather than by physical limitations." He mentions as an illustration, that while it is possible to operate trains at higher speeds than the usual practise, it has not been found economically advisable to do so. I believe the question of higher d-c. voltages will be subject to the results of experience, and whether the limit will be 3000 or 5000 volts, or some other voltage, will ultimately be determined by "broad economic considerations."

In any railway electrification there are certain features which may be considered separately as parts of the general scheme. Under d-c. operation the initial cost, maintenance and depreciation of some of these features are but little affected by the operating voltage, while other features are so directly affected as to be a determining influence in the selection of voltage most favorable to economic results. The power station, high-tension transmission lines and track bonding are in the class of features first mentioned, and to a considerable extent, the substations as well. Sub-station equipment of established type generally increases in cost per kilowatt capacity with the increase in voltage for which it is designed; and while there would be fewer substations at higher voltages, the amount of included traffic usually becomes greater by reason of the longer distance between substations, and therefore there is little or no reduction in the total cost of substation equipment.

The two features principally affected by the choice of voltage are the secondary distribution copper, including contact conductors and the rolling stock. A careful study of the respective merits of 3000 and 5000 volts was made in connection with the Chicago, Milwaukee and St. Paul electrification. There appeared to be little difference in the initial cost as a whole, the reduction in copper at the higher voltage being offset by increased cost of the locomotives. On the basis of 3000 volts the relative value of the different features in respect to each other may be illustrated by the following percentages: the high-tension transmission line complete, about 10 per cent; track bonding, 4 per cent; substations complete, about 18 per cent; the overhead construction, feeder copper and trolley complete, about 28 per cent; and the locomotives about 40 per cent. The 3000-volt copper for feeders and trolley only being something less than 20 per cent, and the locomotives being about 40 per cent it is not surprising that the reduction in copper at 5000 volts would have been offset by greater cost of the locomotive.

Considering depreciation and maintenance, it is better that an equivalent expenditure should be in copper rather than in locomotives which require maintenance and upkeep. To economize in copper and pay an equal amount for more expensive locomotives would be a transaction on the wrong side of the balance sheet.

Mr. Renshaw's comment with respect to 2400 and 3000 volts is in the main well taken. The Butte, Anaconda and Pacific might well have been 3000 volts. Occasions may arise, however, where the use of developed apparatus may be utilized to advantage at some other voltage than that for which it was originally designed,—a case in point is an electrification requiring locomotives with the same tractive power as those used on the Milwaukee, but at a speed of 12 instead of 15 miles an hour. It would be unnecessary expense to redesign this equipment for lower speeds when the same equipment at 2400 volts will give the speed desired.

Within the requirements of railway motor design multiples of 750 volts seem to be about the higher practical limit for advantageous winding. For the speeds usually required it is about as easy to wind a motor for 1500 as it is for 1000 volts, therefor multiples of 600 or 750 volts as a maximum naturally fall into line as the preferred voltages for d-c. operation

Mr. Renshaw in advocating 5000 volts makes this comment,—"With practical apparatus for this voltage available, the problems of distributing and collecting the necessary power for the largest locomotive likely to be required can be readily solved, so that although further increases might be possible they should be entirely unnecessary." There is at present no necessity for 5000 volts to successfully handle the distribution and collection of the necessary power for the largest locomotive likely to be required. The collection of power for the Milwaukee locomotives at 3000 volts is a complete success, there being no sign of arcing at the contact between the pantagraph and the trolley wire in either freight or passenger service. Although the locomotives are equipped with two pantagraphs, a single one only is used; the current taken on the mountain grades being 800 to 1000 amperes, at 15 miles an hour by a single freight locomotive, and the same current at about 30 miles an hour in passenger service. The problem of successful current collection is greater at the higher speeds, and experimentally over 1500 amperes have been collected at over 60 miles an hour with a single pantagraph and no sign of arcing. The success on the Milwaukee is due both to the arrangement of the pantagraph collectors and method of supporting the contact conductor. Each pantagraph is provided with two collecting pans lined on the bearing surface with copper strips, and the contact conductor is two 4/0 copper wires which are in contact with each other in the same horizontal plane. The hangers supporting each of these contact conductors from the catenary are alternated so that the hanger of one conductor is midway the span of the other. The object of this arrangement of hangers being to minimize any inflexibility in the support of the conductors. For the successful collection of current without arcing it is absolutely essential at all speeds that intimate contact be maintained between the pantagraph and the contact conductor, and this can best be accomplished by so supporting the conductors with loop hangers, allowing freedom of vertical movement without the added inertia of the catenary. The upward pressure of the pantagraph should further be sufficient to slightly lift the contact conductors. The contact conductors are, therefore, lifted and carried free of the supporting catenary by the pantagraph in its passage. We found through a series of tests, that the wear of the pantagraph collector and the contact conductor was due not so much to the friction or mechanical wear as it was to the arcing due to collecting current, even an incipient arcing, so small as to be hardly visible, having a destructive effect. As an illustration, when collecting 1000 amperes, the rate of wear with 20-lbs. pressure against the contact conductor was about double what it proved to be at 30 lbs. pressure, the latter being the pressure adopted for the Milwaukee service. Running copper to copper we found, as might have been expected, that lubrication of the contact surfaces was essential to maintaining a smooth surface, and for this purpose a mixture of grease and graphite was used. It might be expected that lubrication would increase resistance of the contact surface. The most careful examination seemed to indicate that the conductivity is rather improved than otherwise. So far as we can judge from the tests, and from other lines operating under similar but less favorable conditions, the contact conductor on the Milwaukee will last for a number of million pantagraph passes.

There is no doubt that substation and locomotive equipment of 5000 volts can be successfully operated. The substation equipment would not differ materially from a 3000-volt installation. The locomotive motors, however, because of the additional insulation required, and doubtless some change in the design would have less power for given size and weight, and in all probability, a greater number of motors would be required for a given service. The locomotive control equipment for 5000 volts seems to be principally a question of the additional space required for insulation and for the more extended arcing of the contactors. Experimental operation of the Butte, Anaconda and Pacific locomotives at 5000 volts gave opportunity of trying out the control devices under conditions approximating service operation. Arcing and flashovers at 3000 or 5000 volts are more startling, but seem to be even less destructive to the apparatus, than at 600 volts. The high-voltage arc seems to spread over more surface with less local burning than at the lower voltage.

The results of operation on the Milwaukee have been extremely gratifying. Nothing has occurred in connection with the use of 3000 volts that might not well have happened with 600 volts. Minor troubles have developed in the auxiliary devices, particularly on the locomotives, which are more annoying than serious, and can easily be corrected.

The regenerative feature of the Milwaukee locomotives has in every way been as successful as anticipated. The eastern grade of the Rocky Mountains is 2 per cent for 20 miles, and both freight and passenger trains are taken down this grade without air brakes more steadily and smoothly than they run even on the level, and without the delay incident to inspection of brake shoes and wheels as required when air brakes are used. On the lesser grades, where an occasional application of air brakes has formerly been required, regeneration is also made use of to control the train at whatever speed desired. The flexibility of d-c. regeneration makes it particularly suitable for the regulation of trains over a variable profile.

I quite agree with Mr. Sprague that it would be unwise to say that 3000 volts is a finality, and having in mind the economic problems that have to be dealt with, and that railroads are operated for profit, there would be even less wisdom in the arbitrary establishment of a standard not based on experience.

Calvert Townley: I can endorse the last speaker's remarks against the establishment of a standard voltage or trying to say now what shall be the limitations of future practise. I believe that the Institute and all engineers individually should encourage every possible advance in the art, and developments such as the one described in Mr. Renshaw's paper clearly indicate that substantial progress is still being made. Every improvement in fundamentals even if accompanied by some unfavorable construction limitations which are not fundamental should be welcomed and encouraged.

In commenting on the necessity for looking at every problem from all angles when selecting a system, the last speaker quite properly favored a greater investment in the excess copper required by a lower voltage system and which depreciates very little, against the same amount put into the increased cost of the motors and auxiliaries of a higher voltage system where the maintenance and depreciation are both greater. It must be borne in mind, however, that a system which permits the use of a higher voltage scores a distinct fundamental and permanent advance in the art while whatever may be the present offsetting disabilities of increased equipment costs, these are largely temporary. We are just beginning to make 5000-volt equipments and 3000-volt equipments are not so very old. The history of all electrical development has shown that we may confidently expect improvements in design which will largely or entirely remove such temporary offsetting disabilities if any, as may now exist. One speaker cited the St. Paul Road as an example to prove that a 3000-volt trolley e.m.f. is high enough, concluding therefore that there is no use of trying to use higher pressures. He remarked that only one single 500,000-circular mil feeder is needed throughout the entire length of line. Without pausing to comment on the advisability of letting the entire service of a large railway system depend on one feeder it is interesting to note that a 500,000-circular mil bare copper feeder, 440 miles long, calls for over 3,500,000 pounds of copper, while with 5000 volts and with the same energy loss the investment in over 2,000,000 pounds of this copper would be unnecessary.

I feel very strongly that the Institute should welcome and in no sense attempt to decry any fundamental advance such as is described in the paper of the evening, and we should congratulate ourselves and the successful designers that such progress has been made possible.

While rejoicing at the recent rapid and marked increases in available continuous-current voltages, it is perhaps interesting to ask why this sudden activity—this very material advance after years of practically no progress when the limits seemed to have become rather firmly established? I find the answer largely in the increased demands of the new field of heavy railroad electrification and the development of the single-phase system which threatened to monopolize this field. The stimulus of competition has supplied the needed incentive to greater exertions in the study of continuous-current possibilities. If continuous-current apparatus was to receive serious consideration in heavy railroading it was necessary that every possible reduction in the excessive costs of that system should be made and every advantage taken of simplification of method. These conditions have not changed. It is still necessary for the continuous-current system to be bettered. A 3000-volt trolley is not good enough to more than incidentally share, much less to monopolize the heavy traction field against the alternating current. It is far from clear that even a 5000-volt trolley e.m.f. will be sufficient to prevail over available alternating-current systems but it is however a long step in the right direction and we should welcome and encourage it in every possible way.

S. I. Oesterreicher: While in Mr. Renshaw's paper only general outlines of the underlying fundamental principles of high-tension d-c. railway practise are discussed, perhaps, it will not be out of place to mention certain details of modern d-c. railroad practise.

Mr. Renshaw does not mention storage batteries in connection with high-tension d-c. railroad work. From this I infer, that Mr. Renshaw does not deem it practical to consider such, for the voltages which are discussed in his paper.

While there are, no doubt, considerable difficulties about a floating battery on a say 3000-volt equipment, however it certainly would be worth while to investigate these difficulties for the sake of the advantages gained from the economic operation of the installation as a whole.

The greatest handicaps for such a storage battery project are purely commercial. Naturally this side of the problem must be determined, from case to case as it is presented, and for which no definite rules can be set down in advance.

From the technical side there can be no question, that it is entirely feasible to build and operate with perfect reliability a storage battery for any reasonable moderately high-tension voltage.

To give this statement some weight, I will cite a 1100-volt d-c. railroad equipment as designed by Mr. Fischer, chief engineer of the Budapest City Railroad Co. This company operated in 1912 about 56 miles of three branch lines, having a total of about 124 miles of tracks.

On one of these lines, with a length of about 30 miles, there are one generating and two substations. Power is generated at 11,000 volts, 42 cycles, 3 phase, and supplied to motor generators in the substations. The generators in the substations generate on this particular line 1100 volts, direct-current.

Upon the d-c. bus is connected a Tudor type 484-cell 1000-ampere-hr. battery which floats upon the system as any other standard battery.

There is nothing remarkable or special about this installation as a unit. The battery is standard in every respect, except the battery room, where the floors and wall are insulated from the building.

Even on a three-wire installation, having as potentials 650 and 1100 volts, there is no difficulty experienced from the battery. The only special auxiliary in this double-voltage equipment is the counter-e.m.f. booster regulator. This set consists of a 600-volt d-c. motor and six generators mounted upon the same shaft. The operation of this set is however standard. Each three generators taking care of one side of the system. The voltage regulation of the booster regulator as well as the load distribution between generator and battery is entirely automatic.

Another interesting feature of this Budapest system is the overhead line construction, with its flexible trolley wire suspension, upon the messenger cable. The trolley wire is allowed to slide lengthwise over the tracks, to adjust itself automatically to the climatic variations, allowing a free contraction or expansion of the wire without additional sagging under the suspension clamps, and from which it follows that sparking is almost entirely done away with. Counter-weights of about 3000 lb. at every mile or mile and a half or so about take care of the even trolley tension over their respective sections.

Benjamin F. Wood: I have been connected with a system that has standardization in fact, and lately I have changed to a system that has standardization, to a great extent, in theory. The trolley car man wants everybody to adopt his standard. I noticed in the first picture which was thrown on the screen that there were four or five voltages shown. It does seem that some standardization is desirable, but I think that the electrical man is getting himself into some difficulty with the railroad people when he talks about cost and the little refinements connected with the efficiency of operation. I made some calculations one time on the electrification of a double-track line, 130 miles long, operating 3000 to 3500-ton trains, at twenty minute intervals throughout the day, at a maximum rating of 0.2 per cent, and found that could be done with 600 volts. The difference in cost between the different voltages was comparatively small, only 2 per cent on the total, and the cost of operation would be only a few per cent. When you realize that the total fuel cost on a trunk line is only five or six per cent of the operating expenses, and you have got to sell electric power to the steam railroad at approximately the cost of fuel when you take over that operation by electric service, you will see that when you come to save five per cent, or ten per cent, even, of this fuel percentage, it is of trifling importance when compared with dependability of operation. That is the primary thing. The railroad man wants something he can be sure is going to operate continuously and reliably, and that is the end to which all efforts at standardization should be directed.

Ernest V. Pannell: If I have understood Mr. Renshaw's conclusions correctly, he is strongly in favor of the motor, insulated for 1200 volts and commutating only 600 as opposed to the motor which operates at a terminal pressure of 1200. Now this operation of two motors in series on a 1200-volt trolley has always seemed to me to represent only half a solution of the high-voltage railway problem. It is expedient where a considerable proportion of the running is on the 600-volt trolley but one usually finds that where interurban cars operate within city limits, the switch over from 600 to 1200 volts occurs at the end of the limited speed area so that the motors take up full speed just as soon as full speed is permissible.

The main problems attaching to the design of high-voltage motors are two; those of insulation and commutation. In constructing a motor which will operate in series with another on 1200 volts, the first problem has to be met. Clearances have to be sufficient to take care of flashover, projections in the interior have to be rounded off and extra slot insulation carried. In a recent instance the slot space factor of a 150-kw., 1200-volt motor worked out at 37.5 per cent whereas the corresponding 600-volt design would probably have a value of 50 per cent; in other words an armature of given size has a capacity 25 per cent lower when insulated for 1200 as compared with 600 volts. Now in making the additional modifications for running the motor direct on 1200 volts the commutator bars have to be increased in number, possibly by 100 per cent and the armature, if a two-turn winding reduced to one turn. Simultaneously however the amperes per motor for a given output are reduced by some 50 per cent this makes it possible to shorten up the commutator by a similar proportion. Although on account of the space required for bearings, fan, etc., it is impossible to add to the core-length every inch saved on the commutator, it will usually be found practicable to increase the core by two to four inches and by this means the armature will carry a greater flux. On the foregoing basis therefore, a motor of given weight will actually have a greater output with 1200 terminal volts than where it is one of a pair designed for working in series on this potential.

As Mr. Renshaw implies, the question of dollars and cents will ultimately settle the maximum voltages for railway operation. We do not run our trains at ninety miles an hour because the cost of track maintenance and power for operation would be prohibitive. Similarly an economical maximum voltage will be evolved beyond which the extra cost and maintenance of the equipment will outbalance the economy on the line copper. Because 1500 volts is about the maximum which can be applied to a railway motor commutator in service with reasonably satisfactory results I would set the maximum desirable trolley pressure at 3000 volts in the present stage of the art.

A. H. Armstrong: There are two rather positive statements made in Mr. Renshaw's paper and to bring them freshly to mind I will quote. With reference to the use of 2400 volts the author states "From a general standpoint, however, while the results have been welcome as a contribution to the development of the art, suitable applications for this particular voltage are apparently somewhat lacking." On the next page the author goes on to state, "For heavy traction on the other hand this voltage is much too low to solve the problem in a sufficiently comprehensive way to attract the investment of capital in electrification. Even 3000 volts, while overcoming the latter disadvantage to some extent, does not do so completely." The author then goes on to make the suggestion that 5000 volts direct current be adopted and standardized as the proper d-c. voltage for electrification work.

A number of years ago on the floor of this Institute the suggestion was made to standardize the 15-cycle a-c. single-phase motor system as the standard equipment for steam railway electrifications. At that time not a single 15-cycle a-c. motor was in operation in this country, and but one installation has been made in the many years which have since passed. To-night we have the suggestion that 5000 volts direct current be standardized although there is onlyone experimental carequipped with 5000-volt d-c. apparatus which has been in intermittent experimental service for a period of a few months.

There are in operation in this country three very extensive railway systems using d-c. motor equipments of 2400 to 3000 volts, and contracts have been let for similar apparatus for two other installations also of some magnitude. In view of these facts it therefore seems pertinent to approach the proposal to standardize 5000-volt d-c. apparatus by asking two questions.

1. What facts are behind the two statements made by Mr. Renshaw in which he broadly discredits 2400 and 3000-volt apparatus as being applicable to main line electrification?

2. What experience is behind the suggestion that 5000 volts be adopted as a standard d-c. potential and what advantages does it offer?

The sweeping statements that 2400 and 3000 volts direct current "are much too low to solve the problem," cannot be accepted without advancing sufficient facts to disprove the economic fitness of the apparatus now operating successfully on three railways and under construction for two more. Especially is this so when one electrification at 3000 volts has a route mileage greater than the combined length of all the electrification thus far completed in this country to date. It is therefore impossible to let go unchallenged the broad statement that potentials considerably higher than 3000 volts direct current must be resorted to in order "to attract the investment of capital in electrification." In the absence of any facts supporting the claim that 3000-volt d-c. locomotives cannot successfully meet the requirements of heavy traction service, it is not out of place to refer to some of the fundamental features of the C. M. and S. P. electrification operating at that potential.

This electrification extends over four steam engine divisions, a total of 440 route miles across three mountain ranges, the Belt, Rocky and Bitter Root mountains, and presents all the problems confronting operation over a broken profile from level track to long sustained grades of 2 per cent. This 440 miles of track is fed from 14 motor-generator substations having an aggregate installed capacity of 59,500 kw. full-load rating. In each of these substations there is one motor-generator set serving as a complete spare so that in normal operation of the road the aggregate substation capacity running is limited to 33,000 kw. The total d-c. load on the 14 substations will probably be less than 14,000 kw., giving a load factor of over 40 per cent of the aggregate running capacity of the substations. This remarkably high load factor is secured by spacing the substations some 32 miles apart as permitted by trolley distribution at 3000 volts direct current. This substation spacing is obtained in most cases with only one 500,000-circular mil feeder reinforcing the two 4/0 contact trolley wires, the exceptions being the 2 per cent grade over the Rocky Mountains and the 1.7 per cent grade over the Bitter Root Mountains, in which locations 1,400,000-circular mil and 1,000,000-circular mil feeder cables respectively reinforce the trolley.

We have then in the St. Paul electrification a good example of what can be done with 3000-volt trolley distribution and the above statement gives evidence that substation spacing is approximately 32 miles, the feeder copper installed is entirely reasonable and furthermore the load factor of the motor generator sets running in the substations under normal service is very good indeed. Furthermore, the 33,000 kw. running in the 14 substations furnish power to 42 main line locomotives and 2 switch engines having a combined continuous rating of 127,000 h.p. or 95,000 kw. which is further proof that the substation spacing is sufficiently great to profit to a large extent in the matter of diversity factor of the several locomotives operating and assigned to each division. A statement of the Butte, Anaconda and Pacific Railway operating at 2400 volts direct current would add further facts to those cited in the case of the C. M. and S. P. and these facts are submitted as substantial evidence that 2400 and 3000-volt direct current are sufficiently high to adequately take care of the demands of main trunk line electrification. The train weight on the St. Paul totals 3500 tons gross including locomotives, and these heavy trains operate against a 2 per cent grade at 15 miles per hour. On the Butte, Anaconda and Pacific trains of 5000 tons gross are being operated against a lesser gradient and the average drop in trolley feeders and ground return on either road will be found to be less than 10 per cent under the average traffic demands and possibly 20 per cent maximum under certain conditions of operation.

It may seem attractive to always consider the use of still higher voltages, but it must be recognized that very high voltages impose their burden of expense and complications upon the motive power and substation apparatus until a point is reached where these costs become so excessive as to more than offset the reduction in feeder copper and other advantages of a high distributing voltage. There is nothing inherently inexpensive in a high-voltage locomotive and there is little saving in the first cost of the entire installation by transferring a certain portion of the initial investment in copper to a corresponding increase in the cost of locomotives which is the result of going to higher potentials.

Referring again to the proposal to standardize 5000 volts direct current, I do not share with Mr. Renshaw the conclusion that this potential is a natural selection or in any way represents the last word in the development of d-c. locomotive equipments Before the decision was made to adopt 3000-volt d-c. apparatus for the C. M. and S. P., exhaustive experiments were carried out at Schenectady with d-c. apparatus operating as high as 6000 volts with an idea of determining if possible the limiting potential of d-c. apparatus. No such limits were discovered, as with the hastily constructed apparatus tested, it was found possible to successfully open 6000 volts on contactors, circuit breakers and fuses assembled for the purpose and furthermore the current used was obtained from motor-generator sets and was of sufficient volume to demonstrate the successful operation of d-c. apparatus at this potential in commercial service. To my mind therefore it is not a question of the feasibility of operating d-c. equipment at higher than 3000 volts, but rather what advantage either in first cost, cost of operation or increased facilities does the adoption of a higher potential offer.

The 5000-volt car fed from a mercury rectifier tube referred to by Mr. Renshaw constitutes a most interesting experiment but in no way forms a sufficiently solid basis for a recommendation to adopt 5000 volts direct current for heavy traction electrification. If facts can be disclosed which will discredit 2400 and 3000 volts direct current then it will be time to consider the initial installation of d-c. apparatus at a higher potential, and its successful performance perhaps in time may lead to the adoption of a general standard d-c. potential higher than 3000 volts. With the facts at hand, however, I see no reason to go to a higher potential than 3000 volts even to meet the requirements of the heaviest kind of trunk line service. In fact there is much more reason to suggest standardizing this potential with the weight of experience behind it than to blindly adopt a higher potential not yet in commercial service on any scale commensurate with the problems to be solved.

Selby Haar (by letter): I should like to have Mr. Renshaw give his reasons for preferring 5000 volts as the standard. Viewed as a multiple of 1200 and 2400 volts it should, apparently, suit him less than 6000 volts, which is derived from 1500 and 3000 volts. Furthermore I do not see that it is obtained by rectification of a-c. voltage or potential any more conveniently than some other potential of the same order of magnitude.

Carl Schwartz (by letter): Mr. Renshaw's paper in calling attention to the successful application for railway operation of direct current of sufficient voltage to compare in ecomony of transmission favorably with single-phase alternating current suggests a potential of 5000 volts as a standard operating voltage.

Without desiring in any way to detract from the value of standardization, I would like to caution against prematurely adopting a standard high d-c. voltage for railway work.

We have in operation a variety of systems with different pressures so that the ultimate loss on account of lack of standardization should not be materially increased if standardization was deferred until we are able to foresee more definitely what the future will bring us in new developments and experience.

Practically all standards are the result of gradual development to a degree where a further increase in perfection or efficiency is either impossible or unnecessary and it seems questionable whether we have reached this point as far as voltage for electric train operation is concerned. Standardization if adopted too early either means a check in progress or if progress is not stopped standardization automatically fails.

The paper further permits the conclusion that if high-voltage direct current is as successful as it promises to be, the future standard system, if such a thing is possible, has increased chances to be direct current rather than single-phase alternating current.

The writer has refrained from taking part in discussions concerning the relative merits of single-phase alternating current as compared with direct current for electric traction. There is one feature in his mind, however, for many years and that is the difficulties connected with the generation of single-phase alternating current. These difficulties are usually reflected by appreciably higher cost of current and greater chance of disturbances in the generating station.

If these difficulties can be eliminated by the use of direct current, still retaining essentially the advantages of single-phase a-c. transmission, a long step in advance will be made.

The principal reason for the relatively limited electrification of steam railroads is not that steam railroad men have failed to appreciate the advantages of electric operation but rather the fact that so far the investment required for all of the electric traction systems has been so high that it was in most cases hopeless to expect a saving in operating expenses to pay for the additional fixed charges.

Mr. Renshaw's paper indicates that this handicap shows signs of becoming materially reduced.

N. W. Storer: The point in Mr. Renshaw's paper that should appeal most to the railway engineer is the portrayal of the great progress that has been made in the car and locomotive equipments for operation on increasingly high d-c. voltages, culminating in the 5000-volt car equipment that has been in operation during the past year at Jackson, Mich. The operation of this equipment has been a revelation to all concerned and it may be interesting to discuss briefly the main points of interest in it, even though it has been partially described in the technical papers.

The development of this equipment was carried out in pursuance of a settled determination to find, if possible, a limit to d-c. voltage for railway purposes, or at least to see if it is possible to arrive at one which would be high enough to meet the requirements of heavy electric traction in extreme instances, and to do this economically. The development of 5000-volt apparatus was started several years ago at a time when 2400 volts was the maximum d-c. potential that had been installed on any line in this country. It was known that an experimental line was in operation in England at 3500 volts, d-c., but no information concerning it was available at that time. Since then, I have had the pleasure of riding on this 3500-volt car and have inspected the equipment. Owing to limitations in the substation generator, the equipment has been operated most of the time with the motors all in series giving half voltage and half speed. However, the commutation of these motors was excellent at full voltage and practically no trouble had been experienced with any part of the equipment, except the dynamotor which was used for furnishing power for lights, control and compressor.

This experience corresponds closely with that of the 5000-volt equipment, except that the latter has no dynamotor.

Any system of electrification, or any voltage that is applied to the electrification of a heavy traction line, should be suitable not only for locomotives, but for multiple unit cars as well. Since the 5000-volt equipment, which has been in operation, consists of four motors of only 100 h. p. each, this can be safely said to be suitable for multiple-unit car operation. In view of the fact that many of the limitations to the voltage of a small motor are much greater than in a large motor, it would appear that it would be still easier to build larger equipments and locomotives, at least the problems of insulation and commutation should be easier.

From Mr. Armstrong's discussion, it may be inferred that he thinks this is a freak construction. Certainly, the designs of the motor and switch groups are quite different from the ordinary types of motors and switch groups for car purposes. However, a careful examination of the equipment will show that the principles are identical with those of the standard well-known types and that the difference is in appearance only; the voltage between commutator bars is no higher than on the ordinary 600-volt motors; the voltages between the upper and lower layers of the armature winding are no greater than with any 1200-volt armature; the number of field coils is less than on the ordinary four-pole moter; in fact, throughout practically the entire motor, the construction is simpler than that of the ordinary 600-volt motor. Practically all that has to be given special care is the insulation of the armature windings from ground. How well this was done may be inferred from the fact that after the car had run over 30,000 miles, one of the armature leads, leading from the coil to the commutator bar, broke off and a hole about 1½ inches in diameter was burned through the armature hood. This armature stood a test of 12,000 volts a-c. to ground without a sign of distress. The commutation has been as near perfect as that of any 600-volt motor, and while there have been cases of flashing in the motor, they have, without exception, been due to abnormal causes, such as reversed commutating fields or broken brush-holder cable, and in no case has there been any damage resulting from this.

The operation of the switches with the arc splitters has been so successful that there appears to be no difficulty whatever in designing switches to handle any reasonable amount of power at this voltage. The arc splitters serve to greatly increase the length of the arc, as well as to chill it. The insulation of the switch group was so perfect that although the switch group frames were grounded to the car structure, there was no case of a breakdown in the insulation until after a 44,000-volt transmission line had dropped on the trolley wire. Then a short time later, one switch insulator and one motor armature were grounded.

The auxiliaries are very well taken care of by the storage battery, which is connected between the main motors and rail. Since the operation of the compressor is delayed until the car starts, the battery is not required to furnish very much of the power for the compressor motor which operates from the current through the main motors. The battery absorbs the excess or furnishes any current that is required above the main motor current. The duty on the storage battery is, therefore, very light. Test on this equipment shows beyond question the possibility of operating satisfactorily with 5000 volts in light service. There would appear to be no reason to doubt that it will operate at least as well in heavy service.

As to the question of standardization, I do not think that we need to feel that Mr. Renshaw had any intention whatever of starting out to show that 5000 volts could be at once adopted as a standard. It is a point to aim at, and it certainly seems more logical to undertake the development of apparatus for a voltage which it is recognized would be high enough to handle any kind of traffic with a very economical distribution system, than to proceed by the small steps which have thus far been made. As a matter of fact, it is recognized that 5000 volts would not be at all suitable for standardization if it could not be made thoroughly reliable. It has not, of course, yet received a test under conditions which would warrant adopting it for general use, or to replace other established systems, but it is certain that a new "bogie" has been established, and it is a voltage beyond which it appears scarcely worth while at this time to go. To be sure, this same equipment was operated at as high as 7000 volts experimentally with entire satisfaction, but this simply shows the factor of safety which the present equipment has.

There has been some doubt expressed by several of the speakers as to the economy of any higher voltage than 3000. The answer to this question depends solely on the cost of substations and locomotives. If the increase in the cost of locomotives is going to be a large percentage of the cost of 3000-volt locomotives, the limit would be very soon reached, but this depends entirely on the type of locomotive that is adopted, and the use of the twin-armature bi-polar motor places a very different light on this question of cost from what would appear with the older forms of motors. As a matter of fact, it appears that the additional cost of a locomotive designed for 5000 volts over that for 3000 volts will be a very small percentage of the total cost, while the decrease in the cost of substation and feeder copper will be a very considerable proportion. It, therefore, seems inevitable that a higher voltage than 3000 will be utilized in the near future, and whether this voltage will be 5000, 4200 or 6000, is, to a certain extent, immaterial.

The advantage of a standard which can be adopted by universal consent is so great that I feel that every effort should be made to reach one at the earliest possible date. If we can get together and decide on something which we feel will be proper and fundamental, as Mr. Townley has expressed it, we will be doing far better than by trying so many steps along the line.

In a paper which I recently presented in England, I stated that in a country where there is an autocratic government, one man can decide on what is going to be the standard. In another country, where there is absolute independence and individual initiative, there may be a hundred different things proposed and used to accomplish the same purpose. In the first case while the man may not decide on the best system, it would probably nevertheless operate more satisfactorily than in the latter case where there are so many different schemes, because the cost of manufacture in the first case will be very much less and everyone will become familiar with the one system and kind of apparatus, and the operation will undoubtedly become satisfactory even though there may be some other system which would have been a little cheaper under the same conditions. At present, we are required to design apparatus to meet many different systems which are really intended to perform the same work. In this way, the cost of development and manufacture runs up to an enormous figure, which the operating companies must eventually pay for.

Mr. Sprague has, as usual, given a spicy addition to the discussion of the paper, although one must search a long time before finding wherein it applies to the subject under discussion. It would appear that he assumes from the fact that Mr. Renshaw, who represents the company which has been responsible for practically all of the successful single-phase installations in this country, has presented a paper outlining the possibilities of high-voltage d-c. apparatus, that the single-phase system is, therefore, dead. A little further investigation of the question will prove to Mr. Sprague's satisfaction that the single-phase system is very much alive.

Mr. Sprague has quoted one of my previous statements in regard to the influence of cost on the system of electrification.

I still hold that the ultimate decision will be based on the first cost and the cost of operation, provided the systems are equally reliable. It is certain that reliability is going to be a prime factor, but reliability is a relative term. There are many things on a railroad which cause delays to traffic. If the number of delays incident to matters entirely apart from the power system is very large in comparison with the number due to the electrical equipment, the question of reliability of the latter becomes of less importance. 600-volt apparatus would doubtless be more reliable than any of the so-called high-voltage or single-phase systems, but the value of the small additional reliability would be far less than the extra cost of electrifying a long line with this voltage.

C. Renshaw: Mr. Sprague's principal point of disagreement, if I understand him rightly is that my simile was somewhat overdrawn, when I asserted that it was practically a universal belief, ten years ago, that 600 volts was the maximum d-c. railway potential, since even at that time he had predicted some of the things which have now come to pass. Aside from this minor point, however, I judge from his remarks that he agrees substantially with the ideas I have expressed.

Mr. Davis points out that with a given train unit the problem of distribution is simplified as the number of tracks increase. A certain minimum size of trolley wire must be used over each track for mechanical strength and with two or three or four tracks, the combined conductivity of the several trolley wires a ndof the various rails in parallel necessitates a less amount of auxiliary feeder than if only a single track were electrified. Stated in another way, with a fixed amount of auxiliary feeder, the greater the number of tracks the lower the voltage which can be used with a given economy of distribution.

While it might be inferred from Mr. Davis's remarks that in view of these facts, he would advocate selecting the voltage for any given electrification according to such circumstances and thus perhaps using 1200 volts in one case, 1500 volts in the next, 2400 volts in a third, 3000 volts in a fourth, etc., I believe that he merely wished to call attention to the principle rather than to advocate such a multiplicity of voltages for future heavy electrifications.

Mr. Davis states also, that since motor-generator sets and synchronous converters are usually designed to stand three times normal load for short periods, there will be no saving in the total amount of substation apparatus by increasing the load factor beyond 33 per cent. This analysis, however, overlooks the fact that the machines which have been designed to stand three times normal load have been made in this way to suit the loads which they must carry and not because such designs give the most desirable or the least expensive machines.

Finally, Mr. Davis states that as a rule the cost of the locomotives for any given electrification will approximate one-third of the total cost and that if there is a material increase in the cost per locomotive for a higher voltage as compared with a lower one, this increase might prove the determining factor. This fact is so obviously true that I thought it unnecessary to mention it. The cost of equipments for 1200 volts, however, is but little more than that of similar ones for 600 volts. Presumably, also, the cost of locomotives for 3000 volts has not proved materially greater than that of equivalent ones for 2400 volts. It seems probable from careful estimates that in view of the improved types of construction that are available, locomotives for 5000 volts can be built so as to cost but little more than if made for 3000 volts, and all of the statements in the paper with regard to the use of 5000 volts have been based upon this idea.

Mr. Potter agrees that my comments on the unfortunate circumstances that have given us electrifications at *both* 2400 and 3000 volts are in the main well taken, and this broad-minded position on the part of a man of Mr. Potter's ability and attainments is the most hopeful sign in the entire discussion. With this point appreciated, everyone must surely see the desirability in future of avoiding similar multiplications of voltages as far as possible, and as it was to point out this fact that the paper was primarily written, I feel decidedly encouraged by this statement from Mr. Potter.

Mr. Potter suggests a change in the last sentence of the paper where I said that if 5000-volt apparatus were "commercially available" such and such would be the case. He suggests the words "commercially economic," instead of commercially available. Such a change, however, would not in any way affect the meaning which I intended the sentence to convey, for to my mind, the apparatus which is out of line in cost, is not commercially available.

Another portion of Mr. Potter's remarks which appealed particularly to me was that in regard to the collection of current. After saying that this had seemed to be a great problem and that some years of study had been given to it, he adds "The solution was found to be rather simpler than anticipated." This sentence appealed to me because I believe that some day I will have the pleasure of hearing Mr. Potter, and some of the other gentlemen who have commented upon the paper, use these same words in regard to the employment of apparatus for 5000-volt direct current and the standardization of voltages for heavy electric traction.

Mr. Townley agrees that a potential of 3000 volts is not high enough to hold the field of heavy electric traction, but he is not sure that even 5000 volts will do this. He announces, also, that he is against standardization, seemingly because he believes standardization tends to discourage advances in the art.

With regard to the last idea it seems to me that just the opposite is true. Nothing tends to encourage the development of an industry so much as a semi-permanence and general interchangeability of the apparatus for carrying it on, and no class of apparatus can be really developed on a commercial basis unless its use for a reasonable term of years is assured. I believe therefore that it would be much more encouraging to the art of heavy electric railroading if, instead of employing a little higher voltage in each successive case, where d-c. apparatus is used, some definite voltage, sufficiently high to meet all reasonable requirements, was generally recognized as being standard.

Replying to Mr. Oesterreicher, I had not mentioned storage batteries in connection with high-voltage d-c. roads, since as far as I know it has never as yet been necessary to consider their use seriously on such roads in America. I see no reason, however, why batteries could not be arranged for 5000-volt direct current if this was necessary.

Mr. Wood has made a good point by indicating that it is not so much the *cost* of electrical apparatus as its *worth* which concerns the railroad man, since the cost of the electrical part of the system is a comparatively small part of the total. "The railroad man", he says, "wants something he can be sure is going to operate continuously and reliably and that is the end to which all efforts at standardization should be directed."

It is obvious that if the skill of the various available designers can be constantly applied to perfecting the details of any given apparatus, rather than to changing its fundamental character, the results Mr. Wood is looking for are more likely to be secured. If the railroad man, also, is offered something that is already in use he can be much more certain of the results he will obtain. I believe Mr. Wood's remarks therefore are strongly in favor of the policy I have been advocating, of choosing the right thing for any given class of work as quickly as possible and then sticking to it.

Mr. Pannell, in advocating the use of motors wound directly for 1200 volts rather than of two 600-volt motors in series, in cases where the cars are not required to run at full speed on 600 volts over part of their route, has overlooked one important fact. Where a manufacturer builds motors for operating on 600 volts, as well as for 1200 volts, a considerable investment in drawings, patterns, tools, etc., can be saved by the use of the same motors with minor changes for the two voltages, instead of radically different designs. In arguing that 1500 volts is about the maximum potential which can be applied to a railway motor commutator in service and that to allow not more than two motors in series he would therefore set the maximum trolley potential at 3000 volts, he has apparently forgotten the double armature motor which Mr. Storer described and which with 1500 volts per commutator and two motors in series would permit a trolley voltage of 6000.

Mr. Haar inquires why the particular voltage of 5000 was chosen, since it is not a direct multiple of 600, 1200, or 1500.

In undertaking to produce d-c. apparatus for a voltage high enough to be suitable as a standard for a reasonable period of years, we started to design our apparatus for 4800 volts, or double the value of 2400 volts, then the maximum contemplated. This was later raised to 5000, however, since it had a more euphonious sound than 4800. As a matter of fact our experimental line has been operated at about 5300 volts and the apparatus was tried on the test track with voltages up to 7000.

I am not particularly concerned with the exact value of the voltage chosen, whether this be called 4800, 5000, 5500, or 6000, since by the term "5000 volts" in the paper, I have intended to include anything in this range. The fundamental point which I have been trying to make, is that *some* voltage in the neighborhood of 5000 should be generally recognized as a standard for heavy electric traction so that d-c. electrifications can be installed with some degree of uniformity, instead of on a basis which will give each one a voltage just enough higher than its predecessor to be different without being sufficiently high to be adhered to in the next case.

Mr. Schwartz is apparently possessed by the same fear which Mr. Townley has expressed, that standardization tends to limit progress. I believe I have covered his points sufficiently in replying to Mr. Townley's remarks.

In referring to the discussion presented by Mr. Armstrong the first thing to be done is to free oneself from the confusion created by his way of grouping 2400 and 3000 volts together as though they were one and the same, instead of being different systems, sufficiently far apart to be entirely distinct and yet so close together that, as emphasized by Mr. Potter, it is unfortunate that we have both of them. Taking up his question, then, as to what has discredited these two systems for heavy electric traction, I would reply that as far as the 2400-volt system is concerned, Mr. Armstrong himself discredited it by ruthlessly abandoning it in favor of 3000 volts when the first real railroad was presented to him for electrification.

As to the 3000-volt system, nothing has as yet "discredited" it. The St. Paul electrification at 3000 volts is a magnificent piece of work, but so is the New York Central electrification at 650 volts, and there is no more reason to suppose now that the former represents the magic limit of voltage for minimum cost than there was a few years ago to suppose the same thing about the New York Central. I believe, in fact, that if Mr. Sprague would hunt up the bibliography with even a small part of the assiduity he has used in preparing his discussion, he could show that only a few years ago Mr. Armstrong himself was just as positive that the 650-volt system was the only rational way to electrify a railroad, as he now is that there is no possible reason for using more than 3000 volts. I have great hopes, therefore, that Mr. Armstrong will keep on raising his voltage and that if we give him sufficient time, it will sooner or later reach 5000 I will hence waste no effort in trying to convince him now.

While it is true that the operation of one 400-h. p. car for 35,000 miles constitutes the sole commercial experience with 5000-volt direct current, this is a much greater experience than was available when the first line was built to operate at a voltage of 1200 instead of 600, or when the first electrification was undertaken using 2400 volts instead of 1200. From this standpoint, therefore, the matter seems in reasonably good shape.

"It may seem attractive", says Mr. Armstrong, "to always consider the use of still higher voltages" but to me it decidedly does not seem attractive and it is in the effort to set others thinking of the obvious disadvantage of such a procedure that all of my energies have been directed. In the period referred to in the beginning of the paper, 600 volts was the established standard for electric railways, so that "an electric railway" meant a 600-volt d-c. electric railway. This particular standardization on 600-volt direct current, was not brought about by action of the A. I. E. E., or any similar body, but by general recognition of the merits of the case by manufacturers and users of the apparatus. It was nevertheless very effective. When it was proposed to build or equip a given line in those days there was no question as to voltage, or system, to confuse the main issue of whether the work should or should not be undertaken, and it was during this period that most of our present city and interurban railways were built.

To establish the same conditions in the field of heavy traction at this time, is of course a much more difficult matter, but there is no question that the advantage to all concerned would be equally great could this be done. It is not my idea that such a standardization could be brought about by any resolution or recommendation of the Institute, and in suggesting the adoption of a standard I had no such action in mind. If standardization comes, it must be by a general consensus of opinion, as in the case of 600 volts, and my real object has been to start such an idea.

Most of the speakers who took part in the discussion seem to have allowed themselves to be misled by the difficulty of the problem. Not seeing any way to bring about such a standardization of voltage immediately, they have felt forced to speak against the necessity or the desirability of it. No great work is ever accomplished, however, without a great deal of thought and planning and dreaming long in advance of the realization, and if I have succeeded in starting some of this thought or planning or dreaming, I will feel that the first steps have been taken.

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ELECTROCHEMICAL INDUSTRIES AND THEIR INTEREST IN THE DEVELOPMENT OF WATER POWERS

BY LAWRENCE ADDICKS

Abstract of Paper

The electrochemical industries have grown to be of great value to this country; they have a fundamental interest in the development of cheap power; they offer nearly ideal power loads of magnitude; they must be located strategically as regards supplies and markets; Niagara power is not cheap enough nor is it sufficient in its present state of development to afford growth to these industries; the industries have so far been hardly strong enough to develop large powers themselves; great expansion should follow the development of cheaper power in accessible locations; and the country is vitally interested in the development of the nitrate industry, which must have very cheap power in great quantity in order to exist. In view of all these considerations, a liberal water power policy on the part of the government would seem to be a step in the right direction.

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THE INDUSTRIAL processes founded upon electrochemistry have a part in the manufacture of a very wide range of commercial products. By definition they all require electric power in greater or less quantity and in many instances power is a large item in the cost sheet. The power requirements vary enormously, however, in different cases, and many other considerations enter into the determination whether a given industry can flourish in a given location. It is the purpose of this paper to point out briefly the interrelation of some of these factors and the interest the industries have in the development of cheap power.

The electric current may be used for its chemical effect, giving oxidation products at the anode and reduction products at the cathode in an electrolytic cell; or it may be used for its heat effect in an electric furnace, where high temperatures and a controlled atmosphere are desirable; or both effects may be utilized, as in the electrolysis of fused salts. Finally, we have the effects of electric discharges through gases.

It is not generally appreciated to what extent electrochemical processes have entered into some phase, at least, of nearly every branch of our industrial life. A small beginning in electroplating two generations ago has developed until the great majority of the copper output of the world is electrolytically refined; silver is thus parted from gold, and gold from the platinum metals, bismuth-bearing lead can be successfully treated, electrolytic nickel is well known, and zinc and tin so refined are appearing in the market. In general, electrolytic refining not only increases the purity of the metal but makes possible the recovery of the impurities as byproducts, thus greatly cheapening the cost of some of the less common elements.

The electrolysis of common salt is the basis of the electrolytic alkali industry, the products of which are caustic soda, the starting point for various chemical industries, and used in very large quantities in soap making, mercerizing cotton, etc.; metallic sodium, also used as a foundation for other products, such as the cyanide so largely used in the metallurgy of silver and gold; chlorates, used in the manufacture of matches, certain explosives, etc.; hypochlorites, of value for bleaching; chlorine, employed as a sterilizing and chloridizing agent and for the formation of bleach.

The electric furnace has created a host of new industries. Very briefly, the chief products consist of abrasives, such as carborundum, alundum, aloxite, etc.; graphite; silicon; ferro-alloys, such as ferro-silicon, -manganese, -chrome, -tungsten, -vanadium and others, which are used in the steel industry for producing sound ingots, hardening, making special steels, high-speed tool steel, armor plate, etc.; refined steel of crucible grade; phosphorus by distillation; calcium carbide, used in the generation of acetylene and in the manufacture of cyanimid; and so on. It is also being tried out experimentally as a competitor of the combustion furnace in the metallurgy of many metals. Used as an electrolytic furnace, we have the very important application to the production of aluminum.

The industrial use of electric discharges through gases is still in its infancy, but we have ozone and nitric acid among the products, the former used for sterilization and the latter as a base for fertilizers and explosives.

This brief review of electrochemical products is by no means exhaustive. If it were followed to a logical conclusion and a list made of all the uses of all the products it would be a formidable affair, but I think enough has been said to establish the first point that I wished to make, namely, that electrochemistry today plays a large part in our industrial life and that its industries are more important than the public at large realizes.

Now every one of these industries consumes large quantities of energy. Starting at the bottom, we have the refining of lead at 120 kw-hr. per ton, and of copper at 300 kw-hr. per ton. Where diaphragms are used, as in nickel refining, the power rises to about 3000 kw-hr. per ton. Where insoluble anodes are used for the recovery of a metal from solution, the power will range from 700 to 4000 kw-hr. per ton, depending upon the metal, the amount of depolarization at the anode, and of course the current density.

Turning now to electric furnaces, an ordinary melting operation, such as casting an alloy or refining steel, generally requires from 600 to 1000 kw-hr. per ton. In the production of ferro-alloys, which is really a smelting operation, a large amount of energy is consumed by the endothermic reaction, and the power used runs from 3000 to 8000 kw-hr. per ton of product, depending upon the grade of alloy made. The aluminum furnace requires 25,000 kw-hr. per ton of product. The electrolytic refining, alkali and aluminum industries require direct current; the graphite, carborundum, melting and ferro-alloy furnaces use alternating current. In general low voltage and high amperage is employed. In the case of alternating current this is readily obtained by the use of suitable transforming units; in the direct-current processes it is customary to connect a sufficient number of cells or furnaces together to obtain a reasonable line voltage. Individual industries in plants of modern commercial size require blocks of energy ranging from 5000 to 50,000 kw., and it is self-evident that the charge for energy in such quantities is a vital item in the cost sheet. And this brings us to the question of what is cheap power.

Twenty years ago Niagara power was cheap, but in the meantime steam power has made such strides that Niagara and similar water power developments can no longer be considered the exclusive sources of electrolytic power. In so speaking I am of course not considering the very low rates which were made on a few contracts in the early days at Niagara, but of the present rate of about 0.3 cent per kw-hr. ($20 a horse power-year). With the very high economy of the large turbo-alternator it is quite possible to meet this figure by locating a plant near some of the coal fields. It is therefore idle to discuss any new source of power higher in cost than Niagara.

It is often suggested that electrolytic plants could be operated to advantage on off-peak power. This is seldom practical. In the first place, to shut the power off for several hours in many cases creates very undesirable chemical conditions; then, in most electric furnace processes there is a loss of heat while standing which calls for the expenditure of excess energy upon starting up; and finally, there is the loss of production due to several hours' idleness to be reckoned with, and in this connection it must be remembered that electrolytic plants generally call for heavy investments, the fixed charges on which need every possible ton to divide by. After these handicaps are properly allowed for, it is only in exceptional cases that a mutually satisfactory contract can be made.

And then we have the power contract to deal with. The owner of the water power generally requires that a fixed minimum annual sum shall be paid regardless of consumption. This is naturally a little hard on periods of low output. On the other hand, excess power is apt to be either subject to prior sale or charged at an excess rate, so that the manufacturer has to balance his output on the tip of his nose, so to speak, if he is going to realize the advertised rate per kilowatt-hour.

Next, we have the difficulty that the power is invariably sold as high-tension alternating current, which imposes various conduction and conversion losses on the purchaser which may easily absorb 15 per cent of the incoming power. The transformers and other apparatus represent a considerable investment, shattering another illusion—that the "other fellow" had to put up all the money. Then in some contracts we mustn't unbalance the phases or let the power factor run off.

By the time all these allowances are made, the power originally spoken of as 0.3 cent per kw-hr. is nearer 0.4 cent, plus a considerable investment, a figure which begins to approach the cost of steam power in the vicinity of New York City, using buckwheat coal; and, as before stated, Niagara Falls is no longer bargain power. This statement leads to a number of questions about as follows:

(1) If cost of power is the great consideration, and Niagara Falls has no longer the cheapest power, why do all the electrochemical industries remain grouped there?

(2) If electrochemical industries have been able to thrive on present power costs, is not the cry for cheaper power merely one for additional profits?

(3) We have in this country a variety of fuel supplies: why are not great central stations established in some of these fields if the resulting power would cost less than water power?

In endeavoring to answer some of these questions, I hope to bring out the main factors which have to be considered in establishing an electrochemical industry.

As to the first question, the cost of power, while important, is by no means the whole, and often not even the controlling, factor and Niagara, while an electrochemical center, is not the sole residence of such industries. There are three main factors to be considered in locating such an industry; transportation, labor and power; and in reality power may be placed under the transportation heading, leaving but two. In any industry, raw materials must be carried to the manufactory and the finished products to their markets. As fuel can be carried and electric current can be transmitted, it is evident that the increased cost of power due to such movements is simply a freight item. The moment this is realized the problem does not differ from that presented by any other manufacturing operation. Where raw materials are bulky and the product and power used are not, the work will be carried on near the source of the raw material, as in the case of a plant for reducing copper from its ores. Where power or fuel is bulky it may become the controlling factor. In zinc metallurgy, for example, the ores are rich and it takes three tons of coal to smelt one ton of zinc. Zinc smelters are therefore located in the fuel belts. An electrochemical instance is aluminum. Here the ore is carried great distances in order to avoid the transmission of 25,000 kw-hr. per ton of aluminum produced. Then again, the process may not greatly change the bulk of the raw materials, as in refining operations, but transportation still governs. In electrolytic copper refining the plants are, with a single exception, at tide water. Here the Western smelters bring the product up to 98 per cent copper. There is but little dead weight in transporting this crude copper, and the silver and gold contents if separated at the smelter would have to travel by express. Also labor and power are cheaper at tide water where the market is, than in the Rocky Mountains where the smelters are. The one exception at Great Falls, Montana, is where an exceptionally cheap water power exists at the smelter, precious metal contents are low, and there is the possibility of considering Western markets and movements via the Panama canal. Finally, labor is a large item. If we assume that a man earns $3.00 a day and that power costs 0.3 cent a kw-hr., the two are of equal importance when an industry uses, on a 24-hour day, 42 kw. per employee. By no means all the electrochemical industries use such a proportionate amount of power. I think enough has been said to show that an appreciation of geographical values is of the utmost importance and that power is of purely relative value.

If we examine the industries grouped around Niagara Falls, we shall find that practically all of them have been created in the last 25 years; that many of them use as raw materials such things as carbon, salt, silica, etc., which are obtainable within a reasonable distance; and that they are chiefly those electric furnace operations which rate among the larger power consumers in the electrochemical list. Now, the investment called for in electrochemical plants is generally high, and it can be readily understood that it is a very welcome lessening of obligation in starting a new industry to be able to cut out the money which would be tied up in a private power plant. Also, really low costs on steam power can not be obtained until a load of about 15,000 kw. is built up. Then, Niagara Falls is in a strong location as far as transportation facilities are concerned. Water transportation through the Great Lakes is at hand and Buffalo is a railroad center. The labor market is also good.

As to the second question, whether 0.3 cent per kw-hr. is not low enough to allow any electrochemical industry to thrive, it is simply a matter of competition. Useful as electrochemical products have proved, they are not necessary to sustain life; we got along, after a fashion, a quarter of a century ago before most of them were heard of. We must remember, however, that every one of these products has had to win its way against competition. Graphite and the abrasives have had to compete with natural graphite and emery; aluminum had wood and copper to displace; the alkali products can be produced chemically; the ferro-alloys can be made in blast furnaces; electrolytic refining had fire methods to compete with; electric steel refining replaced the crucible method; and so on. It is quite conceivable that power costs should be so high that the older processes in some cases might revive. On the other hand, electrochemical processes are in their infancy and a decrease in the cost of power is bound to stimulate new lines of production. It is quite within the range of possibility that many of the combustion furnaces now used in metallurgy can be some day replaced by one or another type of electric furnace. Hydrometallurgy, which is closely linked with electrodeposition, has also a large field before it. The question of electrical action on gases is a most promising possibility for development. Take the fixation of atmospheric nitrogen, one of the largest technical problems which this nation has to face today. We import large quantities of Chilean nitrate every year. Our only local sources are decomposing organic matter and a small quantity of byproduct ammonia salts. Nitrogen is a necessary constituent of fertilizer and is the base of all explosives. The military recklessness of being forced to depend upon imported material for the manufacture of ammunition in these troublous times has recently brought this question very much to the front. There are several methods of fixing the nitrogen of the atmosphere in use abroad. Two of these processes, the oxidation of nitrogen in the electric arc and the conversion of calcium carbide into cyanimid, are suitable for commercial development in this country, and in fact there is already a large plant devoted to the cyanimid industry at Niagara Falls, Canada. The arc process requires large quantities of electric power; several hundred-thousand horse power are so used in Norway. The cyanimid process, while chemical, requires calcium carbide, an electric furnace product, as its raw material. As matters stand today it may be necessary for the government to subsidize this industry to guarantee its required supply of explosives in time of war. If we had 500,000 h.p. available at say 0.15 cent a kw-hr., (a common figure in Scandinavia) this great industry would develop at once on a peace basis on account of the fertilizer demands.

As to the third question, our electrochemical industries are either buying from some water power company or they are generating power themselves from steam. The water power company naturally sells its output for all that it will bring, with a weather eye on the local cost of steam, and very few industries are large enough to save this profit by operating their own hydraulic plants. Unfortunately most of our high-head water powers, which are capable of development on a small scale and with moderate investment, are on the Pacific coast where markets do not yet exist for many electrochemical products. Most of the latter are of such a nature that they serve only as raw material in manufacturing operations conducted chiefly on the Atlantic seaboard. The time may come when various electrochemical industries will associate in a cooperative power development. In this case the eastern coal fields will be carefully considered, especially as many of the processes require large quantities of coal for operations entirely apart from electrochemistry, such as evaporating or heating liquors, reverberatory smelting, etc. Near a sufficient and suitable supply of water for boiler feed and condensing, and close to the coal mines, a mammoth steam plant could certainly give a lower power cost than now obtainable at Niagara. Perhaps the chief objection to such a scheme would be the present unsatisfactory labor situation in the coal fields.

Then we have the various propositions depending on the use of gas. Natural gas is fast disappearing and can no longer be considered for such a plan. The beehive coke oven, which used to be held up as a glaring example of heat waste, is also rapidly giving place to various retort types. The use of producers supplying gas engines begins to lose its attractiveness as the cost of fuel decreases, and placing the steam plant near the colliery deals a heavy blow to this scheme, which offers low fuel consumption as an offset to great first cost and lack of overload capacity. The byproduct coke oven is more attractive, but so far it has been linked up with either the iron and steel industry or the production of illuminating gas, and it is not very desirable to be tied up with another industry and run the danger of being subject to the ups and downs of industrial prosperity in an unrelated field. Then we have our peat deposits, which somehow never seem to receive really serious consideration.

If we knew that there was no hope of getting lower water power costs, I believe some great central power plant would eventually be established. The two stumbling blocks at present in the water power question are government control and the great cost of developing low-head powers. One possible way of meeting the latter difficulty is to consider the value of the development from other points of view, such as irrigation, navigation or flood prevention. All the power plant wants is the potential energy in the water.

Summing up, the electrochemical industries have grown to be of great value to this country; they have a fundamental interest in the development of cheap power; they offer nearly ideal power loads of magnitude; they must be located strategically as regards supplies and markets; Niagara power is not cheap enough nor is it sufficient in its present state of development to afford growth to these industries; the industries have so far been hardly strong enough to develop large powers themselves; great expansion should follow the development of cheaper power in accessible locations; and the country is vitally interested in the development of the nitrate industry, which must have very cheap power in great quantity in order to exist. In view of all these considerations, a liberal water power policy on the part of the government would seem to be a step in the right direction.

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WATER POWER DEVELOPMENT AND THE FOOD PROBLEM

BY ALLERTON S. CUSHMAN

ABSTRACT OF PAPER

The great increase in population of the United States has been chiefly in urban districts while the increase in population in rural districts has been comparatively small. This results in a continuously growing demand for food with a relatively small proportion of our population as food producers. The production of some of our most highly nitrogenous food products has been steadily declining and American farmers have been producing less per acre than European farmers.

The food supply depends in the last analysis upon the plant food supply. The production of nitrogen, which is one of the three principal fertilizer ingredients, is distinctly a water power proposition involving the fixation of atmospheric nitrogen. More than 80 per cent of mixed fertilizers produced in the United States is used east of the Allegheny Mountains, and for the fertilizer problem the water power must be developed in those parts of the country where the demand for intensive agriculture exists. A feasible and proper plan for water power development in this country will have a profound influence on the development and distribution of cheap fertilizer ingredients which are so necessary under modern intensive conditions in the growth of population and its relation to agriculture.

IN OUR centennial year 1876, just forty years ago, Thomas Huxley, the great English scientist, delivered the dedicatory address at the formal opening of the Johns Hopkins University in the City of Baltimore. In the course of this address he gave utterance to the following pregnant words:

> To an Englishman landing upon your shores for the first time, traveling for hundreds of miles through strings of great and well-ordered cities, seeing your enormous actual, and almost infinite potential, wealth in all commodities, and in the energy and ability which turn wealth to account, there is something sublime in the vista of the future. Do not suppose that I am pandering to what is commonly understood by national pride. I cannot say that I am in the slightest degree impressed by your bigness, or your material resources, as such. Size is not grandeur, and territory does not make a nation. The great issue, about which hangs a true sublimity, and the terror of over-hanging fate, is what are you going to do with all these things? What is to be the end to which these are to be

the means? You are making a novel experiment in politics on the greatest scale which the world has yet seen. Forty millions at your first centenary, it is reasonably to be expected that, at the second, these states will be occupied by two hundred millions of English-speaking people, spread over an area as large as that of Europe, and with climates and interests as diverse as those of Spain and Scandinavia, England and Russia. You and your descendants have to ascertain whether this great mass will hold together under the forms of a republic, and the despotic reality of universal suffrage; whether state rights will hold out against centralization, without separation; whether centralization will get the better, without actual or disguised monarchy; whether shifting corruption is better than a permanent bureaucracy; and as population thickens in your great cities, and the pressure of want is felt, the gaunt spectre of pauperism will stalk among you, and communism and socialism will claim to be heard. Truly America has a great future before her; great in toil, in care, and in responsibility; great in true glory if she be guided in wisdom and righteousness; great in shame if she fail. I cannot understand why other nations should envy you, or be blind to the fact that it is for the highest interest of mankind that you should succeed."

Thus spake, almost half a century ago, one of the most prescient and philosophic minds that the world has yet produced. Our population has already risen from forty to one hundred million people, and it is our present, as well as our future task, to feed not only our own teeming populations, but also, in some large measure, a war stricken Europe, and, from time to time, a famine stricken Orient. It is well that we should examine our resources and review what we have done or are about to do with our heritage. "What are you going to do with all these things?" "What is to be the end to which these are the means?"

It is not my present intention to inflict upon this audience a multiplicity of statistical data, but some significant figures must be here referred to as an introduction to the points that are to receive special consideration in later paragraphs. In consulting the statistical data, I have purposely confined myself to government publications of date not later than 1914. The great European struggle, breaking out in the fall of that year, rendered all world conditions unstable and artificial, so that statistics of war years may easily be confusing and misleading.

In the annual report of the United States Secretary of Agriculture, for 1914, we learn that although the population of the United States has increased twenty-three million in the past fifteen years, the strictly rural districts have shown an increase of barely six million. More mouths to feed with fewer husbandmen, is perhaps *the* most important problem of our most modern age.

Again, from our conservative Secretary of Agriculture we learn that: "While there is an increased diversification of agriculture, and both a relative and absolute increase in important products, such as wheat, forage crops, fruits, dairy products and poultry, we have to take note not only of a relative but an absolute decrease in a number of our staple food products such as corn and meats. In the former in the last fifteen years there has been no substantial advance. In cattle, sheep and hogs there has been an actual decline—in cattle, from the census year of 1899 to that of 1909, from 50,000,000 head to 41,000,000; in sheep from 61,000,000 to 52,000,000; in hogs from 63,000,000 to 58,000,000. Since 1909 the tendency has been downward, and yet during the period since 1899, the population has increased over 20,000,000. This situation exists not in a crowded country but in one which with 935,000,000 acres of arable land, has only 400,000,000, or 43 per cent, under cultivation, and in one in which the population per square mile does not exceed 31 and ranges from 0.7 person in Nevada to 508 in Rhode Island. Just what the trouble is no one is as yet sufficiently informed to say. It can scarcely be that the American farmer has not as much intelligence as the farmer of other nations. It is true that the American farmer does not produce as much per acre as the farmer in a number of civilized nations, but production per acre is not the American standard. The standard is the amount of produce for each person engaged in agriculture, and by this test the American farmer appears to be from two to six times as efficient as most of his competitors. Relatively speaking, extensive farming is still economically the sound program in our agriculture, but now it is becoming increasingly apparent that the aim must be, while maintaining supremacy in production for each person, to establish supremacy in production for each acre."

In other words, and I am now speaking for myself, extensive agriculture must ultimately be practised in an intensive manner, if the food supply of an ever-growing population is to be economically produced. I have no desire to take issue with the Secretary of Agriculture in respect to what he has said about the efficiency of the American farmer. We cannot, however, overlook the fact that European farmers are obtaining higher yields per acre on the selfsame soils that supported our own ancestors before their emigration across the seas, perhaps centuries ago, whereas our own agricultural operations began on virgin fields which in too many instances are already run down if not abandoned. If these things are so, lack of efficiency and careless methods of agriculture must be held at least in part responsible for present conditions. It is, however, manifestly unjust to shift the full burden of blame on to the shoulders of the American farmer. Upon capital and government should fall the fuller measure of responsibility in not having long ere this sought methods of providing more abundantly the plant food requirements of the soil. If it is true that before the war Belgium's crops showed the highest yield per acre, it is also true that the Belgian acres used the highest pro rata quantities of intensive fertilizers. It is at least comforting to learn that the total production in 1914 of our own United States in its six leading cereals, aggregated nearly five billion bushels. But in spite of these overwhelming figures, it is foolish to close our eyes and shut our ears to the conditions that have to be met in the face of an ever-growing population and a relative and actual decline in the most highly nitrogenous food products. It is truly written that man does not live by bread alone. Green vegetables and the fruits of the earth, especially those with a high nitrogen content, are and will continue to be as intensively demanded as the cereals. The high cost of living, a most living issue, is pressing its influence upon the consideration of political parties and platforms, but no legislation can correct, no political promises overcome a condition which rests solidly upon the world-old principle of growing demand and diminishing supply.

At this point I wish to take the occasion to state most emphatically that I am not preaching a Malthusian doctrine of hopelessness. If this statement is not made here with sufficient emphasis, it will be said that we, a deliberative body, are looking forward to a condition of imminent starvation. Nothing could be farther from the truth than this. At the present time we are producing in abundance nearly every product and produce that is necessary for our present sustenance and development. I believe that this will always be true, but in order to make it true, thoughtful men will study the conditions and needs of the future and prepare to meet them in advance. To do less than this is to be false to our country and to our posterity.

The question of an adequate food supply for a growing population resolves itself, in the last analysis, into an adequate plant food supply. Unless we feed the herbiage of the earth, we cannot feed ourselves. As almost everyone knows, the three principal plant foods are fixed nitrogen, compounds of the element potassium, generally referred to as potash, and phosphates. For our principal supply of the first two of these mineral plant foods, we are, as is now very generally understood, mainly dependent on foreign sources. It is just this lack of a native supply which the chemists and the engineers of the country are prepared to meet, just as soon as the powers that control our capital, finance and legislation have adjusted their differences of opinion and become prepared to order the work to go on. The main reservoir on which we must draw for our supplies of fixed nitrogen in the future, both for agriculture and for national defense, must be the free nitrogen of the atmosphere. All present signs seem to show that the fixation of atmospheric nitrogen into products of manurial value can be best brought about by the development of water powers properly and economically located and financed for the end in view.

Even if I had already formed an opinion as to the best ways and means for bringing developed water powers most rapidly into operation, I should refrain from such discussion at this time. What we engineers and chemists are most concerned with is that some compromise between widely divergent opinion should be reached to the end that there shall be more accomplishment and less conversation. Given the statistics of annual yield of our diversified crops, and also given the nitrogen content of these crops, it becomes an amusing and interesting problem to attempt to compute the annual waste of fixed nitrogen, or at least that modicum or portion of it which by export or by sewage disposal or any other of the numerous ways is discharged into the ocean or into the atmosphere, never again to return by any natural means to the fields from which it was taken away. Even under the most conservative methods of computation, the figures roll up into billows of ciphers until one gives up in despair, realizing that it is only another method of attempting to sweep out the Augean stables. And in making these statements, I am not unmindful of the fact that through green manuring and due to the action of the nitrogen-fixing bacteria which work on the roots of leguminous plants, we are furnished with at least a slow natural process for the fixation of atmospheric nitrogen. The annual wastage of fixed nitrogen from our soils is none the less appalling. It does not, however, require statistical data or complicated arithmetical calculations to convince a person with common sense that one cannot go on forever drawing capital from the bank faster than it is put in. We owe our soils at least as much plant food as we take away from them, or agricultural bankruptcy is only a question of time. Agricultural bankruptcy spells ultimate starvation and it spells nothing else.

In 1914 we imported into the United States some 500,000 tons of Chile saltpetre at a value of about $18,000,000. It has been estimated that perhaps one-quarter of this found its way to the soil, in addition to such other forms of fixed nitrogen as ammonium sulphate from coke recovery and the various kinds of organic nitrogen, such as slaughter house and other refuse. But all this is not nearly enough. In Norway alone about 500,000 kilowatts are consumed in the manufacture of artificial saltpetre. In the United States proper it is doubtful if any artificial nitrate has as yet been produced on any scale beyond the experimental, and yet it has been computed that every cubic mile of our atmosphere contains enough raw material in the form of free nitrogen to satisfy our total present consumption for more than half a century. I know of no stronger argument than this for the immediate development of our available water powers, unless it be that these same water powers put to work on nitrogen fertilizers could, at the same time, provide the material necessary for the national defense in case of war.

I should like to take this occasion to add my voice to those of many more distinguished colleagues, in pointing out that though it may be considered desirable to develop water powers in this country, it is very important to take into consideration that such water powers should be suitably located, and that the cost of production of electrical energy should be as low as possible. This is particularly true with respect to the manufacture of artificial fertilizer. The cost of munitions matters little in the face of the emergency of war, but the cost of plant food must of necessity always be kept at a minimum. A water power that costs capital a hundred dollars or more per horse power to develop, and that must be rented for from $17.00 to $20.00 per horse power year, will never solve the problem of cheap food production. Some system for developing low-cost water power must be devised, or, as far as the food problem is concerned, we shall never become self-sustaining or nationally independent. Up to 1914 more than 80 per cent of all the mixed fertilizer produced in the United States was used east of the Allegheny Mountains. This point is admirably illustrated in the fertilizer expenditures map taken from the Thirteenth Census of the United States, which will be discussed in a later paragraph. A developed water power in Alaska, Washington and Oregon could have no possible influence upon this condition. To be practical, electrical water power must serve its own market and its own neighborhood, or it might as well be located on the moon. The growing city populations composed of the millions who live in such great cities as Boston, New York, Philadelphia, and Baltimore, do not contribute to the production of food. With respect to food, they are consumers only, and the soil alone can feed them. It is inevitable that sooner or later the potential energies of our great water powers must be harnessed to the end that the nitrogen of the air may be fixed to feed the soils.

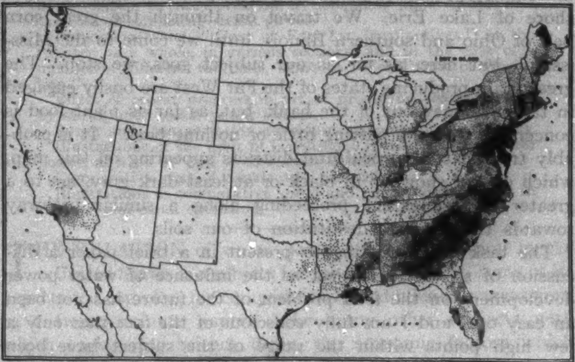
With respect to the necessary supplies of plant foods other than nitrogen, it has not as yet been seriously considered to utilize electric power, but, speaking to electrical engineers, I can say that the extraction of potash from feldspathic and granitic rocks by electrolysis presents by no means an insoluble or even, in my opinion, a difficult problem. It is perhaps the easiest way that has been as yet proposed to obtain potash artificially, which only awaits cheap enough power to become a reality. I need only remind you that in the silicate rocks of which our mountain ranges are composed, there lie dormant untold billions of tons of potash, to show that when the proper time comes we will not want for raw material. On this special topic I am well informed, for I have made a close study of it in the laboratory and in the field for many years.

In regard to our supplies of phosphate, Nature has been extraordinarily generous to this country, and the vast phosphate fields of the South and West are in no immediate danger of exhaustion. In order to make the phosphoric acid content in these phosphate deposits available for agriculture, it is necessary and usual to treat them with sulphuric acid in the manufacture of super-phosphates. It happens, however, that we possess very large deposits of phosphate rock which, while rich in phosphoric acid, contain also as impurities something more than 5 per cent of iron and alumina. Such phosphate deposits as these cannot be treated by the usual sulphuric acid method, owing to the fact that they show a tendency when treated with the acid to become sticky so that they cannot be ground for mixed fertilizer or be properly spread upon the soil. These high iron, " A " phosphate deposits, as they are called, are awaiting an economical process for their treatment, in order to make them available to agriculture. It is my belief that with cheap electric power, this problem can also be solved from the standpoint of electrochemistry.

I shall now present certain data taken from the thirteenth census of the United States (1910), which, in my opinion, shows the urgent necessity for the ultimate application of developed water powers to the food problem of the future. The total area of cereals harvested in 1909 was about 191,000,000 acres as compared with about 185,000,000 acres in 1899, a gain of about 3.5 per cent. During the same period the production increased only about 73,000,000 bushels or 1.7 per cent. The yield per acre was therefore slightly less in 1909 than in 1899. At the same time the population of the United States proper increased from 76 to 92 millions, or 21 per cent. These figures are significant and authoritative, although it is fair to add that they are affected to some extent by bad weather conditions in the corn belt in 1909. The magnitude of a crop is determined by acreage and yield per acre, but the latter factor is the one which really measures in the long run the efficiency of agricultural operations. The yield per acre is affected by some conditions, such as weather, that are beyond the control of man, but no one can say that by the proper use of fertilizer, other things being equal, the production per acre can not be increased many fold. This is indicated also by the fact that European acres before the war were yielding from two to three times that of our own. Leaving aside the questions of proper tillage, plant breeding, seed selection and other important factors in crop production, as not germane to the present subject, let us inquire what the country was doing in the use of plant foods on our soils.

According to the last census report, the total number of farms that reported expenditures for fertilizers in 1909 was about 1,800,000 or about 29 per cent of all farms. The total amount expended for fertilizer in 1909 was about $115,000,000, and the average amount spent per acre of improved land (based on the acreage of all farms) was 24 cents. This average is made up of variations of from one cent per acre in the West, North Central, and Mountain sections to $1.30 in the New England division and $1.23 in the South Atlantic. It is, of course, true that the differences in the expenditures for fertilizers reflect differences in natural fertility of soils, in character of crops grown, in customary methods of agriculture, and in freight rates on commercial fertilizers from mill to market. But nevertheless the value of all crops grown in the United States in 1909 was very nearly five and one-half billion dollars, in the production of which some one hundred and fifteen million dollars-worth of plant food was used, or just a trifle more than two per cent.

I submit that these figures speak for themselves, and that the conditions have not been materially changed in the intervening years between 1909 and 1916. What more strenuous argument is needed for the development of our water powers to the end that they shall be set to work on the production of plant food for the coming generations? Is it not indeed a duty that the present generations owe to posterity?



DISTRIBUTION OF FERTILIZERS IN UNITED STATES IN 1909

Before concluding, I invite your attention to the most illuminating map taken from the last United States census, which gives the expenditure by farmers and the distribution of fertilizers for 1909. This shows at a glance the truth of much that has been set forth in preceding paragraphs, and it shows much more. This map might be made the basis of a popular travelogue. If we use imagination, we can picture to our minds the strenuous drive of the Aroostook County, Maine, potato industry, the efforts of the truck growers of Massachusetts to feed the teeming millions of their congested cities and manufacturing districts. We pick out the high grade wrapper tobacco section of Connecticut, whose product is worth dollars per pound and is found worthy of lavish expenditures for fertilizers. We see the effort to supply the New York, Philadelphia and Baltimore markets, and follow the truck gardens down the Jersey coast to the tip of the Eastern Shore of Maryland. Further south we pick up the tobacco belt and the great region where King Cotton reigns supreme, and this King is powerful to exact his annual tribute of plant food. We see the effect of fruit growing in Florida and southern California, these regions which are still too sparsely fertilized. We can see the sugar cane waving in Louisiana, and even trace the national grape juice from the serried grape vines on the southern shore of Lake Erie. We travel on through the great corn belt of Ohio and southern Illinois, until we come to the Mississippi, but here, as far as our subject goes, we stop. The great grain producing states of the Far West are busily engaged in taking money out of the bank, but, as far as plant food is concerned, they are putting little or nothing back. It is probably true that all agricultural districts appearing on this map, which do not show up in black or at least dark gray, are to a greater or less extent proceeding along a similar pathway towards the ultimate destitution of our soils.

The task of attempting to present in a brief paper a discussion of so vast a subject as the influence of water power development on the food problem of the future has not been an easy one, and I am fully conscious of the fact that only a few high points within the range of the subject have been touched. It is possible, however, that there are many people in this country who have never yet realized that the potential energy of a flowing river can be transmuted into food and sustenance, and thus indirectly direct the vital activities of a nation. The scenic grandeur of a great waterfall may be a national asset, but I am one of those who see an even greater grandeur and a more valuable national asset in vast fields of waving grain and contented, well nourished herds, which mean, as they always have and always will mean, a contented, virile and industrious population.

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RELATION OF WATER POWER TO TRANSPORTATION

BY LEWIS B. STILLWELL

ABSTRACT OF PAPER

The paper discusses the relative importance of water power in its relation to transportation, as depending upon its cost and the cost of competing steam power.

Proportion which "Cost of Fuel for Locomotives" in the country as a whole, in various sections, and in the case of a number of different railroads, bears to "Total Cost of Operation."

Effect of recent progress in art of producing electric power by steam upon water power values.

Power and transportation development on navigable streams.

Illustrations of the limit of investment in developing a water power, as fixed by cost of competing steam power.

Comparative cost of canals and railroads.

Illustrations of comparative speed and power consumption in railroad and canal operation.

THE RELATION of water power to transportation in the United States is a subject far too broad, and in some of its aspects too complex, for comprehensive and adequate treatment in a twenty-minute paper. Like many other subjects with which engineering science deals, the economic factors which determine that relation in any given case depend so largely upon local conditions as to make useful generalization difficult, if not impossible. The best that I can hope to do in the time allotted for this introduction to your discussion of the subject is to point out some of the conditions which determine the value of water power in relation to transportation at the present time, and to indicate roughly how this value may change with progress of the art of producing power from fuel and with changes that may occur in the interest rates upon capital necessary to development.

The relative importance of water power used as motive power to move traffic, in its relation to transportation, in different parts of the country varies, depending primarily upon the cost of water power and the cost of competing steam power as developed by locomotives or by existing or possible steam power plants. Where water power is produced, or may be produced, by building dams on navigable streams, the production and possible utilization of power are interrelated with the problem of inland waterway transportation, owing to the fact that the construction of a dam may be made to serve the double purpose of developing the power and creating a stretch of navigable water.

Cost of Fuel for Locomotives

The following interesting statistics giving for the Eastern, Southern and Western Railroad Districts, and for All Roads, the "Miles of line operated," the "Cost of fuel for locomotives," the "Total operating expense," and the "Ratio of fuel cost to total operating expense," are taken from the report of the Interstate Commerce Commission for the year ending June 30, 1914:

FUEL FOR LOCOMOTIVES, AND TOTAL OPERATING EXPENSES, FOR ALL RAILROADS IN UNITED STATES HAVING OPERATING REVENUES GREATER THAN $100,000 IN THE YEAR.

	Eastern district	Southern district	Western district	All railroads
Miles of line operated........	62,780	46,587	136,257	245,624
Cost of fuel for locomotives....	$ 104,461,133	$ 33,052,970	$105,286,696	242,800,799
Total operating expense........	1,004,620,282	348,295,136	847,397,741	2,200,313,159
Ratio of fuel cost to total operating expense............	10.45%	9.50%	12.40%	11.05%

It will be noted that the "ratio of fuel cost to total operating expense" varies from 9.50 per cent in the Southern District to 12.40 per cent in the Western District, the grand average for all railroads being 11.05 per cent. The total expenditure for fuel for the year is $243,000,000.

Obviously, any substantial reduction in cost of fuel would mean an important saving in total operating expense of our railroads. For example, were it possible, in the case of the average railroad, by using water power to effect an economy equivalent to a reduction of 50 per cent in the fuel bill, a reduction of about 5½ per cent of the total operating expense would result; but unfortunately water power can be substituted for coal or other fuel in the operation of railroads only at the price of an investment in hydroelectric machinery, in transmitting and distributing conductors, and in electric locomotives, so great that a saving of 50 per cent in the fuel bill would constitute in itself an economy by no means sufficient to offset the increase in interest charges upon the investment necessary for electrification. The bearing which such a possible saving would have upon the question of electrifying what may be termed the "average" railroad is shown by the following figures, which are abstracted from a paper "On the Substitution of the Electric Motor for the Steam Locomotive," presented by the writer and H. St. Clair Putnam at the 214th meeting of this Institute. While these figures were prepared nearly ten years ago, additional operating data of electrified railroads now available are corroborative of their general correctness and they are sufficiently accurate for our present purpose. The figures compared are, first, the average for steam operation during five years, from 1901 to 1905, inclusive, as reported by the Interstate Commerce Commission, and, second, the cost of operation by electricity as estimated in the paper referred to.

	Average five years	Estimated cost of operation by electricity
54, Maintenance of way and structures	21.003	22.354
55, Maintenance of equipment	19.524	12.587
21, Engine and round house men	9.451	4.710
22, Fuel for locomotives	11.292	5.702
23, Water supply for locomotives	0.634	.000
24, Oil, tallow and waste for locomotives	0.381	0.250
27, Train supplies and expenses	1.537	1.000
29, Telegraph expenses	1.780	2.000
35, Loss and damage	1.112	0.750
36, Injuries to persons	1.086	1.000
37, Clearing wrecks	0.246	0.200
	68.046	50.553

(The above items are numbered as in the report of the Interstate Commerce Commission, and only items the amount of which is changed by electrification are included.)

The total estimated saving in cost of operation is approximately 18 per cent of this amount, a saving of one-half in fuel accounts, in round numbers, for approximately one-third of the total saving. Reduction in fuel expense which may be effected by utilizing water power, therefore, under average conditions will affect practically but one-third of the total savings due to electrification upon which the question of substitution of electric power for steam will depend in the case of a railroad which may find itself in position to secure the capital necessary to electrify a part of its system.

The following tabulation from the report of the Interstate Commerce Commission for 1914, shows, as might be expected, that the relation which the cost of fuel bears to total operating expense of different railroads varies between wide limits:

STATISTICS FROM I. C. C. REPORT ON RAILROADS, FOR YEAR ENDING JUNE 30, 1914.

Road	Approx. thousands miles of line operated	Cost of fuel for road locomotives millions	Total oper. exp. millions	Ratio fuel for rd. loco. ÷ total oper. exp.	Average tons freight per train	
					(1910)	(1914)
A. T. & S. F.	12.4	5.6	60	9.4	298	357
A. C. L.	6.0	2.6	26	10.0	201	225
B. & O.	8.9	5.6	72	7.8	443	620
C. & N. W.	12.7	6.0	59	10.2	261	348
C. B. & Q.	13.1	5.8	62	9.4	381	479
C. M. & S. P.	14.3	7.75	61	12.7	276	380
D. & H.	1.9	1.9	15	12.7	428	532
D. L. & W.	2.6	2.4	26	9.2	545	652
Erie	4.6	3.2	37	8.7	497	593
Gt. Nor	10.1	5.3	46.5	11.4	520	663
Ill. Cen.	7.7	3.8	51	7.5	364	417
L. V. R. R.	3.4	3.1	28	11.0	536	588
Mo. Pac.	5.0	2.0	22	9.1	240	329
N. Y. C.	9.4	7.0	86	8.2	413	503
N.Y., N. H. & H.	4.6	4.5	49	9.2	293	304
Nor. & West.	3.8	2.9	30	9.7	635	802
No. Pac.	9.7	5.0	41	12.2	429	567
P. R. R.	10.5	9.3	134	6.9	649	729
Reading	2.8	3.2	32	10.0	477	580
Southern	9.8	3.8	50	7.6	237	275
So. Pac.	9.5	4.9	55	8.9	428	431
U. P.	5.7	3.7	29	12.8	432	431
Wabash	4.2	2.3	24	9.6	353	393
	172.7	101.65	1095.5	Av. =9.3%		
All R. R's. in U. S.	245.6	208.4	2200	Av. =9.5%		

It will be noted from this and from the preceding summarized tabulation that fuel cost in general is high upon railroads operating between the Mississippi River and the Pacific Coast, coal being less generally available at moderate cost in this territory than in other parts of the country. For example, while fuel for road locomotives in the case of the Pennsylvania Railroad represents 6.9 per cent of total operating expense, and in the case of the Illinois Central 7.5 per cent, it amounts to 12.8 per cent in the case of the Union Pacific and 12.7 per cent in the case of the Chicago, Milwaukee & St. Paul. While many factors other than the cost of fuel per thermal unit affect these percentages, no argument is required to demonstrate that the cost of coal is a very important factor in railroad operation, and that any important reduction in this cost means increased net earnings, decreased cost to shippers, or both.

It is a fortunate fact, which frequently has been pointed out, that in certain very important sections of our country where coal deposits are lacking, water power is abundant, and since the cost of competing steam power primarily determines the relative value of water power, it follows that the water powers on the public domain, in general, have a relatively higher potential value than they otherwise would possess, owing to the fact that they exist in localities where coal or oil, or both, are relatively expensive. Further, it is to be noted that these water powers are naturally found in hilly or mountainous sections through which the operation of railroads implies the handicap of grades, in many instances heavy, and consequently the consumption of power at a relatively high rate per ton-mile. Broadly speaking, therefore, these mountain water powers in sections where no deposits of fuel exist are of especial interest and possible value in relation to transportation.

The question whether it would pay to substitute electricity for steam as motive power on a given road, or a given division thereof, or even on a certain mountain grade, can be answered only by exhaustive and competent consideration of many factors, among which the cost of power, while an important one, is not necessarily controlling. It is impracticable, therefore, to attempt to fix with precision as a general case the limit of allowable investment in water power development within which a saving for electrification would be shown, as compared to operation by steam.

It may be pointed out, further, that where cheap water power is available in connection with transportation in a hilly or mountainous country, the conditions which control the extension of a railroad system are affected by the fact that cheap electric power makes it practicable to adopt grades exceeding the limits which experience has established in steam practise. The resulting possibility of shortening lines and reducing the cost of the permanent way construction may be important in new territory, although it must be noted in this connection, also, that as regards new lines in such territory over which traffic for a time is usually light, the investment in hydroelectric plant and in railway electrification is generally greatly in excess of the cost of locomotives.

No consideration of the problem of electrifying a railroad, or a division, or a mountain grade, is complete which fails to take into account the fact that the cost of competing steam power has been decreased materially in recent years by improvements in the design and efficiency of the steam locomotive, or to recognize the probability that further improvements will result from the continued efforts of the many able men who are devoting their energies to advance in locomotive design, with special reference to fuel economy; nor is any consideration of the relation of water power to the operation of a railroad complete which omits consideration of the great reduction in the cost of electric power produced by steam-driven generators which has been achieved within the last fifteen years by the substitution of the steam turbine for the reciprocating engine and by improvements in boiler construction and practise. For example, a 5000-kw. turbine-driven alternator today, at its point of best efficiency, will produce a kilowatt-hour using 20 per cent less coal than was required fifteen years ago by the 5000-kw. units which the Manhattan Elevated Railway of New York installed at its Seventy-fourth Street power house, these latter being at least equal in efficiency to any engine-driven units installed in this country up to that time. Moreover, this reduction in cost has been characterized not only by a reduction in the amount of fuel required to produce a kilowatt-hour, but also by a relatively still greater reduction in cost of plant, as illustrated by the fact that a 5000-kw. turbine-driven unit today costs about $12.00 per kilowatt, while the cost of the engine-driven units to which I have referred was $35.60 per kilowatt.

Still further, the development of the dynamo in large and still larger units in connection with the evolution of the modern steam turbine makes it practicable today to realize still greater economy both in first cost and in fuel consumption, owing to the fact that we now can avail ourselves of larger units than were formerly on the market. This additional gain is particularly marked as regards fuel economy. It is probably conservative to say that a large plant, *e.g.*, one of 100,000-kw. output, using large steam turbines, in producing electric power to meet average conditions of demand as existing in our large cities, or in railway service, will use not more than two pounds of coal where the best steam practise fifteen years ago would have required three pounds.

As in the case of stationary steam plants, so also in the case of steam locomotives substantial progress in fuel economy has been made in recent years, and still further progress in this direction must be anticipated and taken into consideration in connection with future utilization of water powers aiming, in whole or in part, to supply electric power for railroad operation.

Power and Transportation Development on Navigable Streams

The relation of cheap power and waterways, as simultaneously developed by the construction of dams on so-called "navigable" streams, is a subject so complex that I can glance at it only in certain aspects. By constructing a dam at a suitable location on almost any stream of reasonable magnitude, a certain amount of power will be produced and a stretch of navigable water of more or less length developed. What the commercial value of the power thus produced will be depends primarily upon the cost of competing steam power as it is produced, or might be produced, in the same locality, and upon the demand for power for industrial and other purposes. What the value of the resulting stretch of slack water may be for purposes of navigation will depend upon so many varying conditions that profitable generalization is practically out of the question. Each project of this kind should receive the most careful consideration, not only from the standpoint of technical engineering, but also from a broad economic standpoint. No conclusion which points to the investment of an amount of capital in excess of that which would suffice to produce an equivalent result as regards the production of power, the provision of transport facilities, or both, can be sound. Railway rates being now subject to regulation by the Interstate Commerce Commission, the argument that the construction of a waterway possesses an economic value to the community in its effect upon railway rates, loses whatever force it may have possessed before a proper method of protecting the shipper was available. To expend public or private money in constructing waterways for such a purpose is to waste a part of that very accumulation of capital by the nation upon which further development of our resources in transportation, in power, and consequently in practically every form of industry must depend.

Vol. 35
1916

As regards power production, investigation of every project aiming to accomplish the double purpose of producing power and providing transportation facilities, should have reference primarily to the cost of competing power produced from coal or other fuel. As regards the utility of any navigable inland waterway which may result from the construction of a dam, it should have reference primarily to the cost and relative advantages, not only of existing railroad facilities, but of new railroad facilities which the investment of equivalent capital might provide. The fact that it has been the policy of the Federal Government to appropriate public money, from time to time, for the development of waterways serving communities more or less local, and that it has not been the policy of the Government to use public money for the construction of railroads, need not and should not influence the investigation of such a project from an economic standpoint. All investment of capital, whether by the Government or by individuals, which results in accomplishing at a great expense a purpose which can equally be attained at less expense, is a waste of capital, which inevitably implies a loss to the community.

Looking at the project, first, as a power proposition, let us determine approximately the amount of investment in the proposed hydro-electric development, including the dam, which may be justified with reference to the cost of competing steam power. For illustration, we may assume that the water power which will result in the construction of the dam is capable of producing, through utilization of modern hydroelectric machinery, a continuous power output of 50,000 kw. A steam plant to deliver this output might comprise five 12,500-kw. units—one of these constituting a reserve to insure continuity of service. Detailed estimates of the cost of such a plant total $3,185,000, which is equivalent to $63.70 per kilowatt, exclusive of the reserve unit. This figure will cover a plant designed and constructed for permanency and for low production cost. Assuming that the available market is such that the annual load factor will be 50 per cent the output of the plant, when fully loaded, will be 219,000,000 kilowatt-hours, and its coal consumption—assuming bituminous coal of 14,000 B.t.u. per pound—will approximate 200,000 tons per annum. Allowing 12 per cent to cover interest, amortization and taxes, the total annual cost of operating the plant and the cost per kilowatt-hour will be approximately as shown in the following table, depending upon the price of coal.

Price of coal per ton	$1.	$2.	$3.	$4.	$5.
Interest depreciation and taxes at 12 per cent	$382,200	382,200	382,200	$382,200	$382,200
Operating labor and material	175,000	175,000	175,000	175,000	175,000
Annual costs, excluding coal	$557,200	557,200	557,200	557,200	557,200
200,000 tons coal	200,000	400,000	600,000	800,000	1,000,000
Total annual costs	$757,200	$957,200	$1,157,200	$1,357,200	$1,557,200
Cost per kw-hr. 50 per cent load factor	0.35c.	0.44c.	0.53c.	0.62c.	0.71c.

From the standpoint of power production, we may now determine the approximate limit of investment in the proposed hydroelectric plant, including the dam and its appurtenances. It may be assumed that annual operation and maintenance will be $1.00 per kilowatt. The permissible investment will depend directly upon the percentage assumed for capital charges, including interest, taxes and amortization. If the required capital can be secured from investors who are content to accept 6 per cent, the total capital charges will approximate 9 per cent. If it must be obtained from investors who have other opportunities for investment where they will not only receive interest on their investment but also will have a chance to double their money (and what industrial or commercial enterprise can be financed by private capital which does not offer this apparent opportunity?) we must assume capital charges at 15 per cent.

The first cost per kilowatt of maximum hour output equals $\frac{\text{Cents per kw-hr.} \times 4380-100}{\text{Capital charges \% of first cost}}$, and the limit of investment theoretically permissible if capital charges are taken, respectively, at (a) 9 per cent, (b) 12 per cent, (c) 15 per cent, is as follows:

Coal at	$1.	$2.	$3.	$4.	$5.
(a) Cost per kw., 9 per cent cap. charges	$157	$201	$245	$289	$333
(b) Cost per kw., 12 per cent cap. charges	118	151	184	217	249
(c) Cost per kw., 15 per cent cap. charges	94	121	147	173	199

The above table, upon the premises assumed, leads to the conclusion, for example, that in a case where coal costs $3.00 per ton and capital can be secured upon terms which make total capital charges 15 per cent per annum, an investment of $147.00 per kilowatt is justified.

Before accepting this or other conclusions from the table, however, it is highly important that the fundamental assumption upon which these figures rest, namely, that the flow of the stream is such that the assumed amount of power (in this case 50,000 kilowatts) will be surely available at all times throughout each and every year, should be verified. The vital importance of this factor, which not many years ago was too lightly considered by some engineers who made themselves responsible for large investments in this field, is now well understood. The failure to establish with certainty in advance of construction the minimum limit of flow has disappointed many expectations and in numerous instances resulted in very serious financial loss. Where water fails, coal must be used, and, obviously, to insure continuity of service a steam plant must be constructed and at times operated to make good the deficit of hydraulic power, even though this deficit should occur during but one year in twenty or fifty years. This means duplicating investment in power plant, and the real value of the water power must be estimated upon a totally different basis.

As illustrating what happens in such cases, let us suppose that, in case of the possible development which we have been considering, the variation in stream flow is such that in an exceptionally dry year, for a short period—perhaps only a few days—water is so low that practically no electric power can be developed. If this possible contingency must be faced, the steam plant must be constructed if it is proposed to supply a power market requiring continuous service, and the permissible economic limit of investment in the water power development is measured by the capitalized value of the saving which would result from using water power as a substitute for steam power when and to such extent as the water might be available. The investment in the steam plant having been made, the possible saving by substituting the water power when available is practically limited to a saving in coal and labor, but it is obvious that the cost of the steam plant, which we have taken to be about $64.00 per kilowatt, must be deducted from the investment which would be permissible if the water power were absolutely continuous and reliable. It is evident, also, that a further sum, representing the capitalized value of the standby charges of the steam plant and of its operating charges while in use, must be deducted from the estimated permissible investment.

If we except the Niagara and the St. Lawrence, there is perhaps no river in the United States the potential value of which as a producer of power is not radically affected by an occasional period of very low water. In the great majority of power developments on such streams it will be necessary to provide and utilize steam power as an auxiliary. Conditions under which this necessity has developed in practise, and will continue to develop as new projects are undertaken, are so varied that it is impracticable in a short paper to attempt a comprehensive discussion of the economic limitations of the problem. For our present purpose the foregoing illustrations of the limit of investment theoretically practicable where capital is available, as fixed by cost of competing steam power, and the general effect upon that limit of any reduction in the amount of water power continuously available, are perhaps sufficient.

It is an interesting fact, sometimes overlooked, that the reductions in cost of steam power which in recent years has resulted from decreased cost and increased fuel economy of steam plants, has reduced very considerably the limits of investments in water powers which, theoretically at least, were permissible, say fifteen years ago. Within that period the cost of high-grade steam plants of large size has been reduced about $25.00 per kilowatt. The amount of coal required to produce a kilowatt-hour has been decreased approximately one-third, and the capitalized value of this saving is a further amount which must be deducted from the investment permissible in developing a water power.

As regards the stretch of navigable water immediately above the dam and resulting from its construction, it is obvious that the value of this depends upon its relation to navigable water above it and below. In connection with the construction of the dam, it is usually practicable to build locks of any required size.

It is not necessary to point out to members of this Institute the fact that no conceivable general system of inland water transportation could parallel the railroads of this country and perform equivalent service. Whatever the policy of our railroads may have been in the past in regard to stifling competition by boats operating on inland waterways, the controlling and fundamental reasons for the abandonment of approximately twenty-five hundred miles of canals, constructed during the first half of the last century by states or by corporations, are to be found not in that policy, but in the fact that the invention and development of the steam locomotive made it possible to build railroads which, constructed at less cost per mile, could operate throughout the year, could transport traffic between two given points in a fraction of the time required by the canal, and at comparatively little expense could provide terminal facilities, practically bringing the railroad to the door of the factory and capable of easy extension to meet the shifting requirements of our growing communities.

Canals vary between such wide limits, as regards width, depth, and topography of the country through which they have been constructed, that averages must be used with caution, but it is interesting to note that, exclusive of the Panama Canal, the aggregate length of canals built by the United States Government up to the present time is something less than 1400 miles, the average cost per mile being approximately $80,000.

We may compare with this figure the average reproduction cost per mile of single-track railroad, as fixed by State commission in Minnesota, Michigan and Wisconsin, in 1907, 1900 and 1903, respectively. The reproduction cost as fixed by the Minnesota commission is $44,888; as fixed by the Michigan commission, $26,138, and as fixed by the Wisconsin commission, $30,910. The highest of these, as will be noted is a little more than half the cost of the average canal (exclusive of the Panama Canal) hitherto constructed by the United States Government, while the average of the three appraisals is about $35,000. On this basis a double track railroad would cost approximately $60,000 per mile.

As regards comparative speed and power consumption in operating by electric power, on the one hand, a canal using 100-ton barges, and, on the other, a railroad, it may be interesting to compare canal operation, using electric power, with results attained on the electrified portion of the New York, New Haven & Hartford Railroad.

The following data are abstracted from a paper by Mr. H. S. Putnam and the writer, presented at the 226th meeting of this Institute, March, 1908, and relate to the canal of The Lehigh Coal & Navigation Company, extending from Coalport to Bristol in the State of Pennsylvania:

Length, L. C. & N. Company's Canal, Coalport to Bristol, 106.2 miles.
Total number of locks: Lehigh Canal, 48; Delaware Canal, 22; Total 70.
Size of Barge used in test: length 87 ft. 6 in.; width 10 ft. 5 in.; draft 5 ft. 2.2 in.

Weight of barge (tons of 2000 lbs.): empty 23.8 tons; load 113.2 tons; total 137 tons.

Watt-hours per total ton-mile, 4-boat tows, about 23 watt-hours.

Watt-hours per freight ton-mile, 4-boat tows, about 33 watt-hours.

Traffic capacity of canal, if all existing locks changed to 4-boat locks: 40 minutes interval between 4-boat tows = 72 boats in 12-hour day, or maximum total tonnage of 72 × 113.2 = 8150 tons freight in 12 hours.

Maximum speed between locks, 4-boat tows: loaded, 3 mi. per hr.; empty, 4 mi. per hr.

Time for trip of 106 miles, about 85 hours down, loaded = 1.25 mi. per hr. average; about 75 hours back, empty = 1.42 mi. per hr. average.

The watt-hours per ton-mile were determined by test, the company having equipped several miles of its canal with an electric haulage system, with a view to determining the advisability of substituting electric power for mules. It will be noted that the energy required per ton-mile, using four-boat tows,—the average load of the barges being 113.2 tons—was about 23 watt-hours for a maximum speed of three miles per hour between locks and an average speed of 1.25 miles per hour between terminals of the canal.

On the electrified portion of the New York, New Haven & Hartford Railroad, during October and November, 1914, the energy consumption per ton-mile of train weight was 27.3 watt-hours in the case of slow freight, averaging 10.85 miles per hour, and 28.5 watt-hours per ton-mile in the case of fast freight, averaging 18.2 miles per hour.* On this part of the New Haven freight runs are comparatively short and power consumption consequently high, and it is safe to say that in the case of a run of 106 miles, under average conditions of stoppage and interference obtaining on double-track railroads in the United States, power required to maintain an average speed of eighteen miles per hour would not exceed that required in the case of The Lehigh Coal & Navigation Company canal in maintaining an average speed of 1.25 miles per hour.

As regards capacity, it will be noted that, even were the locks of the canal between Coalport and Bristol so reconstructed as to permit operation of four-boat tows, the maximum tonnage in one direction during a twelve-hour period is 8150 tons. In this instance the cost of a double-track railroad would not exceed that of the canal, and it is obvious that its capacity would be greatly in excess of the maximum traffic possible through the

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*Article by W. S. Murray in *Railway Age Gazette*, April 30, 1915 canal. For example: a 2500-ton train would carry about 1600 tons of coal, and it would be necessary to pass only five such trains over the road in a given direction during twelve hours to equal the capacity of the canal. On a double-track railroad such trains could be easily operated on thirty minutes headway, which would mean a freight capacity in each direction equal to 4.7 times that of the canal. In the case of the railroad it would be possible, if necessary, to double this capacity by decreasing the headway to fifteen minutes, which, for a speed of eighteen miles an hour, would be entirely practicable.

Without pursuing this subject further, it is evident that, from an economic standpoint, practicable development of our inland waterways is limited to a comparatively small number of rivers, whose channels through a relatively large proportion of their utilizable length are of sufficient depth to permit boats of reasonable draft to navigate them, and which are so located as to permit shipment of heavy tonnage over considerable distances. There are enough of such rivers within the boundaries of the United States to justify the unprejudiced thought of our statesmen and the best efforts of our engineers The amount of money that will be called for in the development of projects of this kind which are economically sound is so great that every expenditure of public or private capital upon power or transportation enterprises which cannot justify themselves when examined in the cold light of economic science, means delay in the development of other enterprises which would constitute valuable additions to our resources in power, transportation and manufacturing industry.

DISCUSSION ON "ELECTROCHEMICAL INDUSTRIES AND THEIR INTEREST IN THE DEVELOPMENT OF WATER POWERS" (ADDICKS), "WATER POWER DEVELOPMENT AND THE FOOD PROBLEM" (CUSHMAN), "RELATION OF WATER POWER TO TRANSPORTATION" (STILLWELL), WASHINGTON, D. C., APRIL 26, 1916.

David B. Rushmore: As we all know, the world in its advance has been marked by certain definite epochs which have been associated more or less with certain inventions. Unfortunately, not all of these have been recorded in the United States Patent Office, because when man invented power and the use of powder, and the use of fire, the Patent Office was not organized.

It is interesting to see that the civilization which we have in this age is sharply distinguished by certain features, and to my mind the particularly distinguishing feature of this age (which we will say runs back something over one hundred years) is the large use of energy and the great advantage which has followed from its use. Our whole civilization is based on the fact that we consume an amount of energy per individual far in excess of the energy which that individual can evolve.

If we had a complete statement of the facts, we would find that in the last one hundred years there has been an enormous increase in the use of energy per inhabitant. The world, and particularly the United States of America, in the past hundred years has gone through a rapid cycle of activities. Their sequence has been exploration, hunting and fishing, lumbering, mining, agriculture, and finally industry, including manufacturing.

The United States is approaching the industrial age, and that is one of the reasons for some of the economic diseases which we may or may not be able to ward off. The food products are falling off, exports of manufactured products increasing. This indicates a change of flow of commodities.

Now, this being an industrial age, and the age being founded upon the consumption of energy, it is rather interesting to show in brief outline what our principal industries are. At the top stands slaughtering and packing, and it is followed by foundries and machine shops, lumber and timber, iron and steel, flour and grist mills, printing and publishing, cotton goods, men's clothing, boots and shoes, woolen, worsted and felt goods, tobacco, car shops, bread and bakeries, iron and steel blast furnaces, woman's clothing, copper smelting and refining, malt liquors, leather, sugar and molasses, not including beet sugar, butter, cheese and milk, paper and wood pulp, automobiles furniture, petroleum refining, electrical machinery, distilled goods, hosiery and knit goods, and a great many others, in which the value of the annual production is over $100,000,000.

Now, if we withdrew the energy from the world, if we for a moment withdrew the energy from our civilization, we would go down like an infant whose food is withdrawn from it. That means that our civilization is dependent on energy, and anything which affects the production of energy seriously affects the continuance of our civilization.

Water-power is one of the sources of energy, fixed as regards location and fixed as regards certain attributes and factors which it involves. Energy we must have for our civilization. And what is the attitude, or what is the relation, of the different factors of chemical industries, of food production, of transportation to the source of energy on which they will draw?

First, the problem goes back to the one which we have often considered, that of conservation. The only way to conserve a waterpower is to use it, and the only way to conserve a coal supply is not to use it. A question that is not often raised, but is involved in all of the papers this afternoon, is the great improvement in steam generating apparatus, both as regards the decrease in cost and the increase in efficiency, but we make a great mistake in making use of the cost of coal instead of the value of coal. If the last ton of coal in the world, the final ton, before we go into something else, cost 80 cents, we can all say that its value will be worth more than 80 cents, so that the value of the coal and oil supply which we are not conserving in any way, in fact, we are now wasting it, by allowing such waterpowers to go unused as might be economically developed cannot be determined by the present cost of coal. We are detracting just that much from some future condition of civilization.

Now, if the government, if a combination of individuals, committed some act which robbed our civilization of some of its food supply, or of some other necessity equally great, or even of some of its pleasures, there would be protest. Just that same cause for dissatisfaction exists against ourselves, for we are all involved, not utilizing in the best way we can the sources of energy which are at hand, and whose use would not diminish their worth, and persisting in the use of sources of energy which may ultimately become exhausted. Take into consideration the per capita increase in coal consumption, increase in commodities, increase in industry and transportation, we can see that it cannot go on forever.

The question of waterpower and its relation to these different energies is this—waterpowers are, some of them, susceptible to present economic development. My personal belief is there are many waterpowers in the United States where power can be developed at the power house for much less than steam will ever be capable of being developed, but water power at the power house is different from water power one hundred miles away. Many of our electrochemical industries could be located at the power house in so far as the simple question of power is concerned. Many plants are already so situated, but in the long run the question of the transportation of materials controls.

I do not place the blame for the lack in waterpower development on any one in particular. As I see it, and under the situation as it has arisen, the people do not understand its value. They sit still, until some one devises and works out some practical way of doing things. When the people are educated, so that they can understand what is going on, then they will take action with regard to the development of such problems.

The railway electrification which has taken place in this country started in the East. The first railway electrification was practically forced by legislation, due to an accident in New York, and that has meant that the railway electrification has been largely based on steam power, on energy derived from coal. There has just begun a larger railway electrification. The transcontinental trunk lines have taken up electrification. The Chicago, Milwaukee & St. Paul is the first one to go into the use of energy derived from waterpowers. They are electrifying 440 miles of their road between Harlowton, Montana, and Avery, Idaho, the first half of this being completed and in successful operation. Some of the results secured are that the cost has been reduced, the weight of the trains increased, and the speed of the trains increased. Prior to the electrification, a considerable proportion, I do not know the exact number, but I think it was not far from 15 per cent, of the locomotives on the railroads were simply hauling fuel for the other locomotives to use. They have been cut out. One of the greatest dangers on the mountain lines is the braking of passenger and freight trains going down hill, and the life of the brake shoe is very short. With electrical motors there is nothing to wear out, not only is the braking done without mechanical friction, but power is brought back in the line.

The very great likelihood is that this road will soon electrify all the way through to the Pacific Coast, and that will force the other railroads to electrification, and force the utilization of these waterpowers, if there is any way of bringing that about. It will require a vast investment, which the railroads have got to provide. If they cannot afford it, they must attract this investment in order to bring about this use of energy. When this waterpower is utilized there will be a saving of other forms of energy to civilization, a saving of coal, which will not have to be burned up until some time later.

The point which we are all looking at is this—the relation of all these factors of waterpower utilization to our modern requirements of consumption. We must bear in mind that once a waterpower is developed into practical operation its supply of energy is continuous and not diminished by time. Some sources of waterpower energy are sometimes inaccessible, sometimes they are expensive to deliver, and sometimes they have a very intermittent stream flow. In certain cases the waterpower can be tied in with another system, a steam station, which, with the waterpower, will develop power for transmission over long distances. In some cases the waterpower plant cannot be physically or economically separated from the steam plant, as a matter of fact, and the question is always before us how best to bring about the most economic utilization of such water-powers and how best to conserve our fast diminishing coal supply.

F. A. Lidbury: There seems to be no doubt from the papers we have heard this afternoon that whatever other applications for water power may be successfully prosecuted in the future the consumption of water power by the electrochemical industry is one that can certainly, given favorable circumstances, be counted upon to grow very considerably. Mr. Addicks has covered very briefly and very concisely the large number of factors which enter into the employment of water power for electrochemical purposes, and the paper is worthy of study because among those who are not closely familiar with conditions in the electrochemical industry it is common to put the whole of the electrochemical industries in one class as power consumers. They are extremely diverse, their requirements in power are extremely diverse, and the relative importance of the factors of power, labor and other items is also extremely diverse.

We have electrochemical industries which have not succeeded yet in obtaining a footing in the United States because their requirements in power are enormous in extent, and because they require the power at a price at which this country is as yet unable to furnish it, and probably always will be unable to furnish it. We have, on the other hand, industries which you could not drive away from this country no matter what the power conditions were, industries such as that Mr. Addicks is associated with, the refining of copper, in which operation the cost of power is such a minor item that they generate the power by steam.

These two classes of electrochemical power consumers, however, stand outside the limits of that group of electrochemical industries which is chiefly located at Niagara Falls in this country. Mr. Addicks inquired why, in view of the fact that the price at which Niagara Falls power is now sold can not be considered low, and in spite of the fact there is a shortage of power at Niagara Falls, these industries do not go to other places. The answer is—they stay there because they are there. Why are they there? Why did they go there? They went there because at the time when these industries were being developed, at the time of their birth, Niagara Falls offered them the most favorable ground which they could select for their development; it offered them a source of power which then appeared to be reasonably large for their needs, a source of power at a cheap price, and a source of power of an extremely reliable nature. To a great extent it is entirely owing to the fact that at the time these industries came into existence that source of power was there in that form at Niagara Falls that these industries now are at Niagara Falls and not, to a large extent, in Europe.

Mr. Addicks inquired why they do not move from Niagara Falls to other parts of the country, particularly to those regions where they could obtain power from steam at a cheap price. That brings me to a point which Mr. Addicks might have expressed a little differently. He compares the cost to an electrochemical consumer of water power and steam power, and taking the cost of water power around $20 per horse power per year, which he presumes to be the present Niagara price, compares that with what he conceives steam power can be generated for in large units. In one case he is dealing with a selling price at one's plant including a profit; in the other with an actual cost. The answer to Mr. Addick's question is that these plants have been moving and are moving from the country. Those of you who are familiar with the conditions of the electrochemical industries of Niagara Falls know that when the restriction was put on the power developments at Niagara Falls, in 1906 and 1907, an emigration of electrochemical plants producing materials not for foreign markets but for American markets started and has been continuing ever since. That gives, as far as one can answer the future by surveying the past, the answer to Mr. Addicks' question—Why do the plants stay at Niagara Falls? The answer is they do not, and they will do so, apparently, to a less and less extent. The reason for this is, of course, as everyone knows, that there is at present a power famine at Niagara Falls, particularly on the American side of the border.

The location of such plants at other points in the United States where cheap water power may be available is only possible in the majority of instances where these water powers are most favorably located. I made some calculations a few days ago comparing the cost of water power with the costs of freight on finished electrochemical products. A reasonably cheap freight rate, as you can all appreciate, is vital in the electrochemical industry. It appeared that a thousand mile haul to the center of the area of distribution would be equivalent to a difference in the cost of power, as a rule, of from $10 to $20 per horse power year; in one or two instances much more.

So far as the electrochemical industry is concerned, this question of water power is a vital and pressing subject. Unless the electrochemical industry is able to get the power as it requires it in economically available locations, that industry will relocate, and to a great extent will relocate abroad. By the time you have converted power into electrochemical products, and utilized those electrochemical products, and have figured what it would mean to this country to stop the progress which those electrochemical products have made possible in the fundamental interests of this country, Mr. Rushmore's $100,000,000 a year will look like nothing.

Henry G. Stott: The question that seems to run through all of the three papers might be put in a few words—How can we get power cheaper? Is there any way in which we can develop power cheaper than it is being developed at present, which will admit of the development of the electrochemical processes? If we go back perhaps we will see why the electrochemical industries today are tending to move away from Niagara Falls.

Fifteen years ago Niagara Falls was unquestionably producing power more cheaply by water than by any other method which could be found in this country. In the meantime the evolution of hydroelectric equipment has gone on quite slowly, as it had a very high initial efficiency. Let us look, on the other hand, at the steam plant. The hydroelectric plant, let us say, has made 10 per cent advance in fifteen years, but in capital cost it has not made any advance at all, if anything the capital cost has gone up, as the cost of labor and material has run up.

Let us look at the steam plant. To begin with, the capital cost of the steam plant in fifteen years has been a little more than cut in two. The next point is that the steam plant is now making power with approximately one-half the coal required fifteen years ago. Those are two enormous points of advantage.

I was very much interested in going over a situation recently which involved tacking on, as it were, a steam plant to a large hydroelectric system. It fell to my work to look into the economics of the situation as well as the engineering possibilities. After going into the situation carefully I came to the conclusion that up to a certain load factor we can today produce power more cheaply, with a lower overall cost, (including fixed charges, and operating cost), by a steam plant than we can by any hydroelectric plant now in existence applied to this particular case.

The overall costs of power were approximately equal at a load factor of 60 per cent. Above that the hydroelectric plant began to show a little better results than the steam plant. Below that point the steam plant was better relatively as the load factor went down.

Now, what we learn from these facts, is simply this—that if we want to produce power at a lower cost than we can do today by hydroelectric plants, we must use some combination of steam and hydroelectric power, the steam plant for the peak loads and the hydroelectric power for that part of the load having load factors of over 60 per cent.

With this combination, as I found in the investigation referred to, the total cost of power, showed a reduction over what could be produced by either steam power or hydroelectric power alone.

There is one feature that Mr. Rushmore touched on, which it seems the whole discussion should go back to, and which we should present to our legislatures and explain the situation as clearly as possible to them; that is, if we can produce steam for the average purposes, for the use of those industries which involves the use of a load factor considerably below 50 per cent, why bother with hydroelectric power at all? There is no use in going into it where the load factor is below 50 per cent. There is hardly a single hydroelectric power left which it will pay to develop if the load factor is below 50 per cent. The conservation of our limited supply of coal, however, demands that every possible means of reducing the annual consumption of fuels should be enforced for the benefit of posterity.

At the time of the last census there were approximately 1,750,000 kilowatts developed hydroelectrically in this country. I wonder if we realize what that means? That means that approximately 20,000,000 tons of coal per annum are saved to posterity. That, it seems to me, is the real point that we should drive into the minds of our legislators if we can,—we should do everything possible to save our limited supply of fuel.

The improvement in the efficiency of steam plants has been remarkable during the last fifteen years, so much so that, as I said before, the total cost of power has been cut in two. I think there is a possibility of going still further, there is perhaps 10 or 15 per cent left to work on with the present cycle, but the important thing, it seems to me, is to stop the use of coal wherever we can do without it, by developing our hydro power. That would look like a good situation for the government to consider in aiding rather than retarding the development of hydro power.

Gano Dunn: The average load factor of all the central stations in the country, including water powers, according to some government figures I recently saw which I trust I interpreted correctly, is under 26 per cent, which drives home the importance of Mr. Stott's remarks about the difficulty of a water power competing in the power market with a steam power when water power is only good, or at its best, at high load factors, and cannot hold its own at low load factors with the present efficiency of steam production.

Those interested in the water powers are keenly desirous of finding some way of getting the cost of power down, in a way that might be regarded as intrinsic, as distinguished from the way Mr. Stott referred to and others have referred to of supplementing the water powers with some auxiliary. An intrinsic way would be the development, of processes that could take secondary power, whose costs of interruption under the secondary power plan would not more than offset the gains due to the cheapness of secondary power.

I hope we can get a full discussion from our electrochemical friends in regard to the degree of interruption permissible, and its economic effect in order that we may study to what extent secondary power can be used to absorb the now wasted surplus power of a great many hydroelectric developments. Such absorption would not only give cheap secondary power but would have a reaction reducing the cost of the primary power; in other words, both services would be considerably reduced in cost.

Mr. Stillwell significantly points out the changed equation between steam power and water power in application to the electrification of railways. It is unfortunate that three-quarters of our power consumption is in the east and three-quarters of our potential water powers are in the west, but if we want to do something about the water power situation, and do it promptly, without going into the realm of doubt, there is a large amount of work cut out by attacking those situations where the water power is actually cheaper than steam power on account of the high cost of fuel, and where the railways would benefit enormously by using such water power as is available. One reason they have not used it in the past has been quarrels among electrical engineers as to which system of equipment was the best. These questions are very rapidly settling themselves. The railroad men, who are conservative, have been deterred from adopting electrical systems, not knowing how soon they might be changed. In introducing electrification upon the railways it has required large amounts of capital, and capital has been difficult to raise in the last decade on account of rate regulations and similar restrictions, as well as on account of the general attitude of the public; and the railways have felt that it would be better to " suffer the ills they have, rather than fly to others they knew not of." It is for us to show that this time has passed, and that the time for the more general electrification of the railways is at hand.

If those interested in water powers, and if those interested in the electrification of railways, especially in the Pacific and mountain states, will devote their energies to bringing the various interests and engineers together, so that there may be mutual understanding, we can at least make a good start by using such water powers as at present can be used to advantage. Once we started, there would be indirect advantages of electrification that will start a general movement and will show that these indirect advantages have, perhaps, been underestimated, and there will then be equipped with water power many railroads which now think they are not quite ready for the equipment.

J. B. Whitehead: It has been emphasized that the cost of electric power from steam plants has been decreasing while that of power from water plants has remained practically stationary. The explanation lies in the general low efficiency of steam plants, offering, therefore, opportunity for improvement and also the lower first cost due to the development of the steam turbine.

The question arises—would it in any way be possible to improve the showing of the hydroelectric plants in the same directions if efforts corresponding to those exerted in the steam problem were also directed to the water plants? While improvements in the efficiency of water power plants, comparable to those possible for the steam plant, may not be looked for, it should be possible, in certain types of plants, to reduce the first cost of the station. Savings should be possible in an aggregation of electrochemical industries and a water plant in which the generating station would operate at moderate voltage and with the elimination of high-tension control and protection. It would also appear not impossible to have the generating station under these circumstances, practically of an out of door type, with such simplified control as would be necessary, located in one of the industrial plants. While this does not attack the larger cost of the dam and reservoir it seems to offer some opportunity for further reduction of cost of the station.

L. H. Baekeland: The standpoint of the chemist or electrochemist can be summed up in this way—we know how to take care of the chemical side of the proposition, but we are enormously hampered by the lack of cheap power. We hoped that you, electrical engineers, were going to help us in our needs. But when you talk so hesitatingly about the possibility of our water powers being cheapened, and, on the other hand, when we consider that our increasing steam power plants will exhaust so much the sooner our available supply of coal, I must say that I feel somewhat disappointed.

The situation is as follows: In some of our electrochemical industries, we are suffering from lack of abundant power even at high prices, say $20.00 a horse power year. The case has been very well stated by Mr. Lidbury. There are certain electrochemical industries where we can afford to pay relatively well for power, provided we get the power at the right locality, the right point for the market, the right point for freight, the right point for raw materials, and the right point for labor. Niagara Falls is one of those places, but the amount of power produced is all taken up, and further development is prohibited by law. Then there are some industries which could not live in Niagara Falls, even if you could supply them with all the power of Niagara Falls, because the price of power there is too expensive, and I cannot better illustrate this than by taking the example of our contemplated nitric acid supply in relation to the defenses of the country. When it comes to making nitric acid for war purposes, it does not matter how much it costs, because it then can be made regardless of cost. Nowadays the people who are fighting in Europe do not figure how much it costs them; someone else will have to pay for that. For example, phenol which in times of peace is rated expensive at seven cents a pound when it is to be used for peaceful industrial purposes was found cheap enough for the making of explosives in time of war at $1.75. The same thing can be said of nitric acid. The Germans, when they wanted nitric acid, did not discuss the question of the cost of power; they simply erected steam and gas power plants as fast as they could so as to become independent from Chile saltpeter in their nitric acid supply. But there is a more important question in connection with this subject, a subject of far-reaching national importance, and that is the production of cheap nitrogen-fertilizers. I am sorry to have to say that in connection with the production of cheap fertilizers, the problem looks much more difficult, because for this purpose, power should not cost more than five or six dollars per horse power year.

There is one point of view which has not been brought out here; our more expensive water powers in the United States, as compared to those of other countries, are mainly due to the fact that in this country there are always more contemplated enterprises looking for capital than there is money available. The business enterprises of the country are chronically short of money. They carry on so many enterprises and do this as quickly as possible, and this increases rates of interest; furthermore, our methods of banking are rather wasteful as compared with those of Europe. The result is that when we erect a water power the fixed charges which are incurred are much heavier than what they are in Europe for similar enterprises. Our rates of interest here are very high. In Europe people were glad to invest money at three per cent in various real estate enterprises, and in water power developments. In this country, by the time you float the bonds and give the usual rake-off to promoters, bankers and brokers, and after you consider a lot of side issues that are involved, your water power is already carrying fixed charges of $9 per horse power year, and this charge is fastened on the enterprise before you start to operate. This fact makes an enormous difference when we come to consider the cheapening of water power. Who is going to change this and how is it going to be changed, is a matter on which I cannot advise. Our bankers will have to use less wasteful methods and perhaps the Government may have to do its share by utilizing its excellent credit so as to obtain money at low rates of interest.

J. J. Carty: One of the purposes of this meeting was to call attention to the method of making the work of the bankers less wasteful—if that be a proper term to use—by establishing water powers upon a stable basis where the investor could know where he stood from one year to another. Money can be obtained in this country at low rates of interest or at high rates of interest, depending altogether on the certainty of return and the amount of return.

Owing to the obstructions which have been placed in one way and another about the development of water power, prudent investors and conservative bankers, whether they be located in Europe or in America, have found that only a high rate of interest would attract the people away from more stable investments into the vicissitudes of water power development. If I understand the character of these papers submitted today, and the general situation, the main object is to remove the uncertainties which entangling legislation has cast about the development of these water powers and then the bankers and investors will be in a position to reduce the cost of these hydroelectric powers by furnishing capital at a lowered rate of interest commensurate with the lowered risk, which would certainly ensue the moment that stability enters into the chaotic legislative condition.

L. S. Randolph (by letter): Mr. Stillwell overlooks one or two points in regard to the locomotive situation, which I think should be dwelt upon.

The largest locomotives that we have been able to get only give about 4000 or 5000 h.p. and that seems to be the limit for the present length of locomotive.

Six drivers in series, or coupled by one set of rods have been used but were not found successful, five are being used on some of the Western roads where very heavy grades are concerned, but as a rule four drivers coupled together or the consolidation type, seems to be the limit and in the Mallet many of these are running back to three pairs of drivers coupled together, although the Henderson Mallet on the Erie has four pairs of drivers coupled together, having three sets, making twelve pairs. This seems to be the largest locomotive so far and the problem comes to "what is the limit in length?" as it is practically impossible to increase the cross sectional area of the locomotive, and therefore increase its size in that way. It is as high now as the bridges and tunnels will stand and as wide, and any increase in that direction would mean an entire rebuilding of the permanent way.

So far, the voltages now used permit 9000 h.p. and this has been transmitted by one wire, two wires, of course, would double this, and with higher voltage and smaller amperage still greater h.p. could be transmitted, and with motors under each car, as in the case of street railway cars the limit is almost infinite.

Another point that should be considered in figuring on the economy is that the coal consumption is really a comparatively insignificant item. If one studies the development of the steam locomotive he will find that for years and years, in fact, up to the last five or ten years comparatively little attention was paid to the coal consumption. This was due to the fact that the addition of one or more cars would add to the income of a railroad enormously greater amounts than the cost of the additional coal; so that all the development was towards increasing weight, size, lessen track resistance, etc., so as to get the highest possible hauling capacity for a locomotive. Some five or ten years ago the limit of the size of the locomotive was reached, and therefore the limit of the size of train it pulled. Attempts were made then, not to reduce the coal consumption so much, but to get a larger capacity out of the boiler and a larger h.p. capacity out of the coal consumption. We had from this, the introduction of super-heated steam and feed-water heaters, which were adopted not so much towards the saving of coal as for the increased capacity.

The application of electricity to steam railroads is indicated at the present day wherever the density of traffic makes it impracticable to handle readily the traffic with the steam locomotive, as a case in point, it is stated that on the Elkhorn Electrification of the Norfolk & Western Railroad in West Virginia, four or five electric locomotives handle the work that required seventeen Mallets of the largest type.

Wherever such a state of affairs exists as just mentioned, electrification will give large returns on the investment.

Lawrence Addicks: I think we must all be struck in this discussion with the philosophic tendency which it has taken. It shows that the engineer of today has to be a political economist, a conclusion at which he has been too long in arriving.

As to Mr. Lidbury's discussion I think it is safe to say that power could be sold for $20 a horse power year from a large plant, meaning perhaps a 25,000 or 30,000-kw. plant, but I qualify that to this extent, that we assume the prices for fuel, labor, etc., that prevailed up to a short time ago, and not the high prices that are prevailing temporarily on account of the war situation.

As to what Mr. Stott said about the load factor, of course, a number of us in the electrochemical industry feel that we have a 100 per cent load factor, and the question does not enter there as in public utility work.

As to what Mr. Stillwell said about interruptions of service, my feeling is that it is not practicable to talk about diurnal interruptions, in order to decrease the consumption of power, of three or six hours a day—I do not believe it will work out satisfactorily, except in some possible case such as the carborundum industry, where the whole furnace is torn down after a certain number of hours run. I do think there is a possible solution, which seems a little fantastic. Suppose we took Niagara Falls and put the whole four million horse power in water wheels, and that it was agreed that the plant should be shut down every Sunday morning, for say six hours, so that we could turn the water back into the river. In this way you would satisfy everybody. You would satisfy the power people, because they would get the power which they require. You would satisfy the conservation man, because he would have the scenery, and he could see it once a week. It would satisfy the hotel man, because more people would come up to see the river turned back than came to see it running in full force.

Allerton S. Cushman: Mr. Addicks has referred to his impression that the gentlemen who have discussed these papers have treated them from a philosophical viewpoint. Thathas not been the impression made upon my mind by most of the discussions. It struck me that many of the engineers were principally interested as to whether water power or steam power would be the best paying investment under present load factor conditions. My own mind has been more exercised with the probable future needs and conditions of the country than with dividend prospects under present conditions. If it is true that we are to expect a population of two hundred million people in this country within the next half century or so, it is about time to begin to study the power requirements of the future and to discuss water power development from a somewhat broader viewpoint. For my part, if it requires for the time being a subsidiary steam plant to make a water power plant pay, I would rather have it that way than allow our water to continually run to waste. This may not sound very practical, but surely there is such a thing as building and preparing for the future. Moreover our electrochemical industries need water power, and already in some cases are going abroad to find it. I am at least practical enough to realize that if we are to have cheap water powers we must have cheap money to develop them. The government can borrow money at low rates, or the government could guarantee or endorse water power bonds under properly safe-guarded conditions. I for one can see no harm in such a suggestion, and would advocate such a plan if I had the opportunity. To my mind it is one way of keeping the government out of business, but I confess I would rather have our government develop those water powers that ought to be developed than not have them developed at all. The government might build the dams and lease the power under proper regulation, but this would mean the use of government money, with the usual pork barrel danger. Under a guarantee plan, the government would use nothing but its credit unless some water power failed to earn the interest on its bonds. Why should Norway get cheaper money than we for water power development? Some way out of this situation ought to be found, for many people in this country believe that these things are worth doing and worth doing now.

L. B. Stillwell: The last speaker, Dr. Cushman, made a statement which it seems to me is fairly debatable from an economic standpoint. To my mind the proposition that the government should endorse water power bonds is economically as unsound as—possibly it is worse than—the proposition that the government should build a system of canals to parallel our railway systems. The government never yet has been able, I think, to father industrial enterprises or transportation enterprises with that degree of scientific discrimination which is essential to a right result.

Private capital in this field needs no endorsement by the government. What it wants from the government is security of tenure—definite title or definite lease—so that it can at the start before making its investment estimate all the essential factors which it must know in order to justify investment.

Until we have evolved a very different system of economic administration of government in this country, I should be sorry, indeed, to see the government embark upon a plan of endorsing water power bonds.

I do not know that there have been any points in my paper which have been discussed that I need refer to. Our president has touched with great clearness and with emphasis upon the point made by Dr. Baekeland in regard to the high rate of interest. I believe that the high rate of interest which we have to figure when estimating a water power development would be materially reduced if we could secure a definite tenure and if we could feel sure that the going concern would not become an object of unjust attack through the power of taxation. It is the fact that these factors are today uncertain which in my experience frightens investors away from water power development.

The one thing that we need to do—we engineers and all of our citizens who understand the economic facts—is to educate the public and to assist our legislators to get the economic facts in proper perspective in order that we may secure legislation that will permit us to go ahead. It is nearly eight years now since the agitation began in regard to western water powers, and it would be hard to name a water power of importance that has been taken up and developed *de novo* during that time. There are a number of cases where plants have been extended, where a growing business and the fact that money was already invested compelled an extension, but the number of new ventures is not great.

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WATER POWER AND DEFENSE

BY W. R. WHITNEY

ABSTRACT OF PAPER

The United States has no adequate domestic source of fixed nitrogen. Nitric acid is an absolute necessity in the manufacture of any form of explosive as well as in the production of dye stuffs. Ammonia or nitrate compounds are in increasing demand as fertilizers. The present dependence upon Chile is a menace in case of war and involves the payment of export duties and profits amounting to nearly $5,000,000 annually in times of peace.

Home production is wholly a question of initiative and proper utilization of water power. Failure to establish the industry in the past has been due to economic conditions, such as the relative proximity of Chile and the impossibility of competing with the cheap water powers of Scandinavia as well as the lack of a near-by agricultural demand. The growing need for fertilizers, the desirability of establishing a dye-stuff industry and especially the feeling of uncertainty in international relations make a reconsideration desirable.

National safety demands the development of a nitrogen fixation industry whether it be self-supporting or not. But, the industry once established, the products would be of the greatest value in times of peace and many other industries would be stimulated thereby. Thorough industrial organization is the best preparedness for either peace or war.

Each of the processes under consideration has advantages. The problem is many-sided and far reaching and hence it is very desirable that the various government departments concerned, those of the Army, Navy, Agriculture, and Interior, with their skilled staffs and expert knowledge, should cooperate in determining the course to be taken. Immediate action is very important, since at least two years will be consumed in getting any process available into operation, after a decision is reached.

VIEWS on the relationship between our water power problems and the problems of national defense are as different as they are numerous. No one is safe in assuming that he has, for long, held the correct view, for the correct view changes rapidly with the conditions, and these changing conditions are not entirely under control. There are a few facts which it may be wise to review because of the changing conditions referred to, and because all of us are interested in national welfare.

A group of these facts which relate to what we call fixed nitrogen should be foremost in our interest. They may be briefly stated as follows. The United States has thus far practically no natural sources of niter or other form of fixed nitrogen, nor has it developed any sources of the artificial products beyond the recovery of ammonia from gas-liquors and coke ovens.

Niter has always been the *sine qua non* of explosives, and with all the complicated developments which have taken place in the field of explosive manufacture, nothing practical has been produced which does not depend absolutely upon niter.

The old type black gunpowder which contained niter, sulphur and charcoal, used the salt as such. The later smokeless powders made use of the nitric acid produced from niter by means of sulphuric acid. The cellulose, the glycerine, and the toluol in gun cotton, nitroglycerine and trinitrotoluol respectively, are wonderful substitutes for the sulphur and charcoal of the former explosives, but what we may call the pepper in the powder has always been the nitro group from the niter.

This means, to those who are considering the question of preparedness for defense, that our sources of niter need a lot of insurance. It is not at all inconceivable that our present available supply of niter in South America might become closed to us in the event of war.

The problem of a home source of niter is an old one in the United States. The material has long been used by our fertilizer industries. Organizations representing agricultural interests have tried to bring about reduction in cost of fertilizer necessities —phosphate, potash, and nitrate or ammonia. We have plenty of phosphate rock in the United States, so that freight rates will apparently be the determining factor in the extent of use of this fertilizer ingredient. In the case of potash we are in bad shape. We have some unlocked sources, but nothing comparable with the German supply. We must learn how to cheaply separate potash from our feldspars, our seaweeds, or our ocean waters, and there seems little chance that this will be economically done very soon.

But when it comes to nitrate and ammonia, it is distinctly up to us. The cost will depend on the way in which we use our water power. The raw materials come from the air and the water, and ought to be free to us. At present we are subsidizing the Chilean government at the rate of $2.25 per ton, or nearly one and one-half million dollars a year for export duty, besides paying a profit of five to ten dollars per ton to the producers. This amounts to, say, five million dollars annually.

In addition to our fertilizer interests, the country has become greatly interested in the aniline dye and chemical industry question. No single chemical is so generally important to this industry as nitric acid, and with us it is all obtained from niter. This fact seems to be an additional reason for attempting to round up our local needs for fixed nitrogen, determine the advisable steps to take, and quickly take them.

It is practically true that the aniline dye industry is essential to the manufacture of modern explosives. The identical materials which are developed for dyes, now constitute the basic ingredients of the picric acid, trinitrotoluol, and tetra nitro methyl aniline used in the present war. The coal tar products, the acids and the apparatus are common to both dyes and explosives. For this reason, if we are to be efficient, if we are to have plants capable of producing explosives in large quantities when needed, then those plants must be producing useful chemical and dye products in times of peace.

If it were only necessary to dam the small water courses and pump the air through some sort of simple apparatus, in order to get niter more cheaply, the work would be easy. The question is in reality very complicated. It has never seemed worth while to dam the waterways to make niter in this country. In the first place, our farms, except in certain long-tilled or special localities, have not fallen so low in productivity that it pays the farmers to meet the prevailing costs of artificial fertilizer. This condition is a continually changing one, and it is always changing in the one direction. We shall as surely have to come to the extensive use of artificial fertilizer as have all the older countries. Our western grain and corn states are now producing only about half as much per acre as are the eastern states, and the difference is in fertilization.

Secondly, we have been able thus far to procure Chilean niter for our limited explosive and chemical manufacture, while the processes for obtaining nitrogen compounds from the air have been in a state of flux or development. It was a peaceful world-economy which established the first practically operative and successful nitrate plant in Scandinavia. There such plants are close to the cheapest water powers, remote from all other sources of nitrate, and near the best markets. Norway's water powers differ essentially from our own. Nowhere in the United States, not even at Niagara, are there existing grouped conditions such as could compete successfully for cost of power with Norway.

This is not generally remembered, but to engineers it should be plain. In Norway there was the fortunate combination of exceedingly elevated water level, of quite dependable and high rate of uninterrupted flow, with immediate ocean shipping facilities and a world's hemisphere of well established market close at hand. An expensive dam, or any dam at all was frequently unnecessary. Building sites were probably donated. Fertilizers were most extensively used and most of the world's chemicals and dye stuffs were made in the adjacent countries. Under such conditions there was apparently no reason for our country's doing this work, and that is why it has not been done.

It is the new conditions which make reconsideration worth while. One of these new conditions is our recently acquired feeling of uncertainty as to the permanence of peace. Another is our growing need for fertilizers, and a third, our desire to insure our textile industries by producing our own dyes and chemicals. Probably every human being on the earth today who has reflected at all, has been astounded at changes which a few months have produced in the most civilized countries of the world. It is not surprising that some of us should look about more or less nervously to see if our powder is all right.

Judging by past events, I think we are justified in imagining conditions which might effectively interfere with our continued supply of Chilean niter. Difficulties might arise before the salt is mined, as was the case with potash in Germany before the war. Transportation troubles from interference on the ocean, or trouble in Panama might be effective in shutting off our supplies. Perhaps the danger is slight, but if our importations of niter should cease, then all our efforts at dye stuff manufacture would fail, and all our efforts at national defense, beginning with diplomacy and ending with torpedoes, would be as useless as a poem on Spring. If we cannot shoot a gun, explode a mine or fire a torpedo without nitrate, we ought to be sure of our nitrate before we are forced into war. We need powder before we need soldiers or guns. Evidently this is a matter for mature deliberation on the part of those best fitted to weigh the possibilities.

Our requirements seem to suggest some early and effective type of cooperation between the department of the Interior, the Agricultural Department, the Army and the Navy, which departments are most intimately interested and best equipped to form opinions on the separate parts of this subject.

It is not my intention to consider the different ways of making nitrates, but a few words will show how rapidly the industry has recently advanced.

Since the experiments of Bradley and Lovejoy at Niagara, the Birkeland-Eyde electrical process has come into extensive commercial use in Norway. The Schonherr process, another arc process, has been developed in Germany, and the Pauling process in Austria. The cyanamid and Haber processes for ammonia combined with some form of the Ostwald process for changing ammonia to nitric acid, have both contributed to Germany's nitrate needs. The cyanamid process, using electrical power for making the calcium carbide, which is later employed for chemically combining the nitrogen of the air, was said in 1914 to be represented by 14 different plants, representing an investment of $30,000,000. Since the beginning of the war, this process has been greatly augmented, apparently beyond any other. At the present time, Germany is probably using artificial nitrates exclusively, and the allies are beginning to employ them to a lesser extent.

It is because no group of our national representatives is likely to know all aspects of the nitrogen fixation problem, that the assistance of different interests and departments seems worth acquiring. It seems certain that our demand for nitrates for use in fertilizers, in heavy chemicals, pharmaceuticals, and dyes in time of peace, together with our possible needs for ammunition in times of war, would justify radical steps which any one of these apparent demands, taken alone, might not warrant. It is also probable that if our peace needs were properly taken care of, our war needs would be assured by the identical plants and processes.

It has been suggested that in an emergency, our electric street car and city lighting plants could quickly be turned into nitrate producers. A suggestion of this sort should be analyzed for our government by those competent to judge of the possibilities, and not be left to analysis by a pitiless fate.

It may be worth while to offer an opinion on a few of the questions naturally asked nowadays by the engineer concerning the possibilities of nitrate production in the United States. In times of peace and with present synthetic processes, commercial success is not possible if the electrical power costs are as high as fifteen dollars per kilowatt-year, and there are no profitable by-products. At about half of this rate one or more of the present processes might possibly compete with the natural ante-bellum prices. This could not be done by the use of small isolated plants, nor less than full day load of power. In other words, it would not attract those who ordinarily sell electric power.

This is not the nation's question, however. It is more a question of whether, in times of dire necessity, we could at some inconvenience and high cost, effectively produce within a reasonable time our own requirements of niter. Could a part of existing electrical equipment be quickly utilized for this purpose? Under such conditions would a part-day load be permissible? Could coal be used for power? I do not answer as an expert, but I think that we may safely say that it would take us a couple of years to get under way with the manufacture on any appreciable scale after the delays which would certainly be connected with our decision to start, were passed. The cost might not be relatively greater than are the increased costs of many other products during war time. Electrical equipment already installed might in some cases be employed, but in all probability this would be called upon for other uses with greater advantage to the country. As most of our industrial plants would have to do what they could best do, it seems probable that entirely new plants for nitrate would be called for. I believe this has been the experience abroad. In any of the synthetic processes, extensive and special types of apparatus are necessary: special transformers, special combustion chambers, large capacity air-liquefiers, etc. In the absence of water power such a plant could operate on steam power, but should be placed as near as possible to a coal supply. The possibility of utilizing waste coal, if there is any such thing nowadays, is worth looking into in connection with this question. It does not seem probable that part-time load is practicable even in war time, for the production of nitrate. By the arc process, something like three kilowatt-years may produce a ton of nitric acid, but when the demand amounts to two or three hundred thousand tons of acid per year under war conditions, and requires in that case the twenty-four-hour continual operation of over half a million kilowatts, the impracticability of getting any appreciable proportion of it from the off-peak power of present plants seems apparent. It is only fair to note that one of the processes is said to produce the acid at nearly a sixth of this consumption of power. But in this case, the operation in conjunction with existing power plants seems still less possible on account of the nature of the process.

Nowadays the essentials of national preparedness seem to require longer periods for accomplishment than formerly. When it takes years to build a battleship, war is not a brief siege. The art of successful defense has become a slow and subtle one. It starts with the high school and the education of children. It gets its main strength from the masterly control of technical industries. It owes its effectiveness to novelties in ways of killing, and its staying powers to business foresight and discreet banking policies. It has been well said in this connection that "there is one line of action which we ought to begin at once, and that is, we should begin at the bottom and prepare our industries."

It has also been pointed out that, strangely enough, many of the most useful modern chemical requirements of war are also the leading chemical products of the industries of peace. The chemist sees that sulphuric and nitric acids, chlorin, caustic soda, gasoline, benzol, phenol and toluol, perhaps the most industrial of the compounds in peace, are also the most extensively required in modern war. Similarly, the engineer knows that the modern air hardening tool steels, the modern lathes, the newest boring mills which industrial advance has developed, are now the necessities of munition production. So that industrial activity is a healthy type of national preparedness for both peace and defense.

But for national preparedness, our industrial activities should be comprehensive and cooperative. Whole fields of national interests should not be left entirely untouched because some other country is already profiting in them, as in the case of nitrates today. When it comes to national defense, we must ask ourselves what necessary supplies may be cut off by war. It is for this reason that England, Australia, Canada and Japan have already established national research organizations.

Preparing for defense is consistent with keeping at work in a proper way along the lines of peaceful, healthy industry. In this way it bears on the subject of water power. The engineer will always have the feeling that the power of falling water is a continuing loss except when it is doing useful work. This is inseparably connected with his first lessons in mechanics and thermodynamics, and is probably right. If a single manufacturing company owned our farms and waterways, it is probable that for reasons of efficiency it would make all the available falling water do the work needed to maintain the fertility of the soil or produce useful products. This would only be doing in a broader way what the potentates of Egypt and Assyria had to do centuries ago, when their irrigating systems were built. But we live under a representative form of government, where the difficulties and delay of getting constructive activity are what it costs us to be democratic.

At least two great processes for fixation of nitrogen have been offered to our government in the past few weeks. I refer to the arc process of the du Pont Company and the cyanamid process of the Cyanamid Company. These are essentially different. No brief discussion can bring out their relative values to our country. I consider both of them of the greatest importance to us.

The duPont process, yielding nitric acid directly from the air, calls for cheap water power. Used in conjunction with the production of explosives and the manufacture of chemicals and dye stuffs, it would be a great boon to America in times of peace, and invaluable in war time. The enormous facilities of such a company, widely interested in large scale chemical production and with one of the largest experimenting organizations in America, would certainly bring the arc process much nearer to that high condition of efficiency which the theory of the process predicts and which sometime will be realized somewhere—I hope in America. There is every reason to expect that there would result the evolution of as many new and useful products and processes as are being continually produced in Europe. Several hundred thousand kilowatts are now employed by the arc processes abroad.

The cyanamid process also calls for cheap waterpower and in large quantity. This process seems, at the present stage of things, to be of the greatest importance to our fertilizer industry because of its economical production of ammonia, the form of fixed nitrogen commonly used in commercial fertilizers. The manufacture of nitric acid and ammonium nitrate for explosives by this process is apparently easy and would be economical at power costs which we ought easily to reach in this country.

It is stated that there were somewhat over 200,000 h.p used by the cyanamid process abroad in 1914, and in the past eighteen months Germany has invested $100,000,000. in this work.

These are both tested processes, and we are interested in their present, and even more particularly in their future developments. In any undertaking by our government which involves the granting of special water power rights, the people should want foresight coupled with active, constructive work. It seems as though we might fairly expect sometime a change in the public spirit, which now usually views almost any large manufacturing undertaking with animosity and adverse criticism. Possibly through the study of these immediately pressing problems of explosives, dyes and fertilizers by our most competent and interested government experts, sound business criteria may be established for the nation's benefit.

Personally, I have a fear that we are forever shortsighted. I am afraid of the need for national defense which may come upon us like a thief in the night, from war declared in a day, because I fear that impotency which is spread over a century and never really discovered until too late. The most imperilled country of the present war is learning more about national defense than we are at present, and is not likely to forget the lessons. New industrial processes will continue to be improved by those people who are now actively engaged in them. The more extended become the details, by-products, contingent interests and economies in any such line of industry, the more difficult becomes the start in it by an outsider. It is not out of the question that ten years from now the commercial sources of nitrate will be Germany and Chili. The artificial processes will certainly be improved. The natural source will about as certainly deteriorate. What will we be doing in the meantime? It may be entirely safe to depend indefinitely on Chilean supply, but the question should be decided for our country by those who are responsible and will give it careful consideration.

I believe effective good could be accomplished by quick cooperation between those different government departments where lie the greatest direct interest and knowledge. One of these is the Department of the Interior, under which come the group of experts of the Bureau of Standards and the Bureau of Mines. These certainly possess men interested in industrial chemistry, well equipped, and anxious to serve. The Bureau of Soils of the Department of Agriculture has also a corps of men equally well fitted for this work, and particularly interested to that part of it referring to the fertilizer problems. The Army and Navy Departments, busied with the multitude of normal duties of defense, might still lend a great deal of aid and pressure to this cooperative problem, without having to produce the same kind of chemical and engineering experts found in the other departments. The country ought to be satisfied with the joint conclusions of such representatives of its interests.

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THE WATER POWER SITUATION, INCLUDING ITS FINANCIAL ASPECT

BY GANO DUNN

ABSTRACT OF PAPER

The endeavor of this paper is to present, from the point of view of the engineer, certain aspects of the attitude of capital towards water powers. Actual and threatened laws, popular prejudices, and some cases of unprofitable developments in the past, have retarded the development of water powers, but there are also physical and natural difficulties which handicap hydroelectric as compared with steam-electric plants, and make it essential that a reasonable profit in promotion be offered, in order to induce investment.

The cost of water power is rising, on account of the increasing cost of labor and materials and increasing taxation, and the efficiency of the utilization of water power has practically reached its maximum. On the other hand, the cost of steam-electric power is falling, in spite of a steady rise in the cost of coal, because continual improvements are being made in the efficiency of conversion of heat energy into mechanical power, and still further progress is to be looked for. To offset the disadvantage of the increasing cost of water power there is the possibility of utilizing large amounts of secondary power from hydroelectric plants for industries and process purposes that do not necessarily require continuous power.

The hydroelectric plant usually requires about three times the capital investment needed for a steam-electric plant of equal capacity, and the activity of capital in a hydroelectric plant is very low, much lower than in a steam station and in almost all other branches of industry.

State regulatory bodies have hampered water powers by not recognizing the distinction between bond interest as a compulsory expense paid as the rent for money loaned, and dividends as an earned reward for the risk of the business and skill in management. Another factor that must be more clearly determined in order that the hampering effect of uncertainty may be removed, is the length of time a permit or franchise may run before recapture clauses can take effect, and the question whether these provisions should not cover the power development in its entirety.

Water power should be developed as a matter of conservation, to save our coal supply that is being so steadily depleted. This purpose cannot be served unless the attitude toward water power development is changed and some of the present restrictive factors ameliorated so that investors in water power bonds will be satisfied with five per cent interest instead of requiring seven per cent because of the risks they incur at present.

ALTHOUGH the development of water powers is almost wholly a matter of civil and mechanical engineering, their interests have been largely in the hands of electrical engineers. Until electrical engineers created the art of transmitting power over long distances the usefulness of water powers was local and the extent of their development did not exceed one million horse power in the United States.

During the past two decades electric transmission has extended the commercial water power radius from a few miles up to say two hundred. As the art of electrical engineering has progressed and water power has consequently been transformed from a local peculiarity or advantage to an almost universal utility, an intensive development has taken place, energizing for useful purposes thousands of miles of transmission highways and almost innumerable distribution networks with power which formerly wasted itself in the erosion of stream beds and the heating of of their contents.

The profession of electrical engineering has been stimulated by the reaction of this development and has in turn come to depend considerably upon it. Electrical engineers regard the welfare of water powers as identified with the welfare of a large part of their own activities.

The relation of the American Institute of Electrical Engineers to the government of the United States in connection with water powers is an enviable one and is highly valued by the Institute's 8000 members.

In 1911 the National Waterways Commission of the 62d Congress invited the American Institute of Electrical Engineers to send representatives to the hearings of the commission in Washington. In response, the governing body of the Institute created a special Committee on the Development of Water Powers, authorizing it to testify before the commission and put its expert knowledge and experience in every way at the commission's service.

The services of this committee, composed of the country's leading technical experts on water power, were appreciated by the commission and led to the extension of other invitations to the American Institute of Electrical Engineers to send similar representatives to congressional and departmental hearings in Washington in connection with water power legislation. Among these invitations was one from the Secretary of the Interior, one from the House Committee on Arid Lands, one from the

Senate Committee on Public Lands, and more recently one from the Portland Conference of Western Governors, and others.

The governing body of the Institute has continued its special committee in consequence of these successive invitations and in view of the apparent appreciation on the part of the government that the services rendered by the American Institute of Electrical Engineers were scientific and professional and not commercial or political, that its committee dealt with fundamental engineering and economic principles of hydroelectric development that were outside the field of controversy, and that the function of the Institute being scientific and professional and not commercial or political, its status was one involving a high degree of disinterestedness in respect to matters on which its technical advice was sought.

The present meeting of the American Institute of Electrical Engineers in Washington is held under the auspices of this committee and is devoted to an engineering and economic discussion of water powers in the hope of turning all the light possible upon the subject.

As indicated by the duties honorably discharged by the Special Committee on the Development of Water Powers, the engineer's function has become considerably broader than one of pure engineering. By a group of promoters seeking capital, the engineer is usually engaged to make preliminary studies and trial designs until he selects the most advantageous site for and determines the most satisfactory miminum cost of a given development. His work, however, does not stop here, for he is called upon next to make studies of the probable market for power and to estimate expected revenue and operating expenses, including taxes and depreciation, and further since the relation of engineering and economics is so intimate, the preparation of the economic prospectus usually falls to his lot.

With such a prospectus the promoters solicit the support of one or more investment bankers, and the name and standing of the engineer is an extremely large factor in establishing the confidence of the bankers and obtaining their recommendation of the securities of the project to their clients. The criticisms and objections which the bankers constantly raise in reply to the proposals of the promoters have to be answered largely by the engineer, who often reforms his designs many times and has to prove exhaustively his estimates of revenue, capacity, operating expenses and other items before the bankers take up the project, if they do. Generally speaking and especially in recent years not more than one project in a hundred passes muster.

The engineer therefore usually develops a relation to the financing of water powers, which finds him on behalf of his employers knocking at the doors of capital and using all the abilities he can honorably employ to invite for his client's project the confidence and support of the experts of capital, and he thus acquires a knowledge of the conditions required by capital to be met before financing can be accomplished and he is enabled to take a broader view of the water power situation than one that is merely an engineering view.

The other papers presented at this meeting deal with the value of water powers to the electrochemical industries, to the food problem, to increased transportation and to national defense. In this paper I shall endeavor to present very briefly, from the point of view of the engineer as derived from experience, certain aspects of the attitude of capital towards water powers.

It has already been implied that no matter how useful a public service a water power might perform, no matter how great the need of a community for cheap power to invite industrial development, no matter how powerful the river nor high the falls, nor anxious the promoters, a water power plant will not be built unless the investment banker or his equivalent supplies the means.

The investment banker, generally speaking, is not a capitalist, but a captain for the capital of others. They follow his leadership so long as his record warrants it and they gladly accord him a commission in return for sound advice and guidance as to yield and security for the investment of their savings. These others are countless and are in part scattered throughout the earth. The complicated interrelations of capital among the great capital-producing nations are at once intimate and delicate so that capital may truly be likened to an international fluid, quick to flow towards its level of advantage and equally quick to cease flowing when that advantage diminishes. Prior to investment, capital is above the law. It must be consulted and courted or it cannot be won, and it usually requires of a suitor a good previous character. These are facts, no matter what may be our individual theories of government, of economics, or of social relations.

Part of the acknowledged "water power situation" is due to the scarecrow of financial losses which, contrary to popular information, have been suffered in water power investments. In cases where losses have not been sustained the actual yield as compared to the expected yield has been very generally disappointing. It seems conservative to assert in respect to a majority of water power investments today, that if the holders were not already in they would not go in if they were free to repeat their investment. Investment bankers of a decade or more ago sometimes piloted their clients with honest confidence into water power projects sound in the prospectus, but so disappointing in the light of later reality as to cost them their financial leadership and render their successors increasingly conservative.

There has been a considerable degree of popular prejudice and misapprehension that conceives water powers to be almost illegitimately profitable. It has had a share in making them the prey of local hold-ups for necessary real estate, flowage rights, relocation of railroads, local taxes and damage suits. But the most serious cause of the above kind that is responsible for the "situation" consists of the inhibition imposed unintentionally, or perhaps it would be better to say unwittingly, upon the investment of capital in water power enterprises, by certain laws, administrative regulations and precedents.

These laws have been both actual and threatened, and in many respects a threatened law is worse than an actual one in the check it gives to investment. Among such actual or threatened laws are those which, limiting the tenure of a grantee, provide for recapture without compensation or with only such compensation as would involve serious loss, or for the recapture of only a part of a system at a fair value for that part, but that part so essential that without it the whole system could no longer thrive.

There is a large group of legislative proposals that look upon water powers as a source of taxation or of government profits through the sharing of earnings. They lay a tax upon energy output, gross receipts, installed capacity or first cost of a development, which tax, although appearing small, amounts to a burdensome and deterrent proportion of the net profits after bond interest.

The grantee is required to construct at his own cost extensive locks and navigation works in cases where he might seem in justice rather to deserve a subsidy for his service to navigation through the erection of a dam that increases the navigability of the stream for many miles and assists in the regulation of its floods. These services, it would seem, should at least relieve him of the burden of additional cost for the locks, which is a drag upon his profits.

Among other menaces to the security and yield of water power capital is the reposing in an administrative officer of the government of a discretion which, while presumably it would never be abused, permits the possibility of abuse by some one of a numerous succession of incumbents, and often therefore in effect causes the title to millions of dollars worth of property to rest upon normal individual discretion instead of upon definitely stated laws that permit the whole of a given future to be securely calculated upon. While clothed with great powers, such officers do not have the co-relative power to make agreements or stipulations that may be relied upon as binding the government.

There are also agitated serious objections to the combination of adjacent hydroelectric systems, on the ground that this permits monopoly and may be used to enhance the price of power and light to the consuming public.

With commissions for the regulation of public utility rates in practically all of the states of the Union, the combination of water powers can have no other effect than benefitting the public, for on most fundamental engineering grounds combination either actually reduces operating cost or does the equivalent of it by increasing output for a given capacity. It increases the insurance of continuity of operation and permits reduction of reserve capacity. It reduces the proportion of steam auxiliary power and enables advantage to be taken of excessive rainfall in one area to make up for occasional deficiency in another. The joint cost of distribution lines is diminished, regulation of pressure is improved, and the utilization of powers otherwise too small to be successfully utilized is made possible.

The objection to combination seems to be based upon analogy to combinations in other branches of industry and ignores fundamental engineering principles, especially in the presence of protecting state commissions. Successful opposition to combination could only result in increasing the burdens both of the public and of the developments.

Many others of the actual or threatened provisions are not only deterrents to investment, but are at the expense of the public. In this class fall all forms of taxes on output or development previously referred to. It is sometimes erroneously thought in proposing legislation of this sort that these taxes will be borne by the owners of the enterprises, but they are in fact passed on by them to the ultimate consumers. They are added to operating expenses and rates to the public are increased proportionately. The increased rates check the growth of manufactures and the increase of the use of light and render the community less attractive than other communities where, either through absence of tax or through natural advantages, lower rates obtain. With the increasing use of power in manufactures, the attraction of manufacturers to a locality is vitally affected by the rates for power that can be offered. Federal laws proposed for the taxation of water powers have naturally applied only to water powers under jurisdiction of the federal government. They inequitably leave untaxed and free from such discrimination competing private water powers and water powers under state jurisdiction.

It seems difficult on the part of many to accept the conclusion that by the control of rate commissions water powers are forever prevented from becoming bonanzas to their investors. Other kinds of public utility corporations are seen to be duly regulated, but there lurks a suspicion that water powers may form exceptions. While the consequences of this doubt contribute to a complacent retardation of development, the benefits of water power development to communities of large population do not seem to be adequately appreciated.

In some of the governments of Europe so greatly are the benefits of development esteemed that water powers are encouraged.

In addition to the laws, prejudices and past financial history that have retarded water powers, there are physical and natural difficulties of a very real sort which render a reasonable profit in promotion requisite to induce investment.

Power developed by a hydroelectric system must be based upon the minimum or nearly the minimum flow of the stream, unless great cost for storage is warranted. The dam, however, must be strong enough to withstand the stream in flood, often 50 to 500 times the minimum flow. A water power is liable to suffer not only from lack of water in dry season, but it is often partly drowned out at times of flood when high tail water reduces the hydraulic head. For these and other reasons most water powers require auxiliary steam power for reserve.

A large part of a hydroelectric power development consists of transmission lines exposed to lightning, wind and sleet. A water power, unlike a steam power, cannot be begun in a modest way and allowed to grow as its market gathers. The real estate, dam, rights of way, transmission towers and many other portions of the development must initially be of ultimate capacity and cost, hence during the early years there is usually a period of waiting for the growth of market when expenses often exceed income and owners must not only go without their profits but must often put up funds to tide the project over.

For taking the construction and operation risks and the risk of delayed development of income, to say nothing of the risks of title, taxes and adverse legislation, it can readily be seen that the profit required to tempt investment into hydroelectric projects must be at least as great, if not greater, than that offered by other utilities or industrials.

So far there have been dealt with only the checks to hydroelectric investment arising from actual or threatened legislation popular prejudice and construction risk, but, especially east of the Mississippi River where three-quarters of the mechanical power in the United States is consumed and where there are still undeveloped large resources of water power, there is an additional check that daily speaks with a louder and louder voice ruling out the water powers—even if financing were obtainable—in favor of steam produced from coal.

Increasingly large numbers of water powers that a few years ago would have been considered worthy of development by conservative financial authorities, assuming all legislative and administrative hindrances removed, are now ranged in the unworthy class because they do not meet the supreme test to which every water power project is put in the engineer's office before it can get even to the preliminary prospectus stage. This test is a comparison of the cost of the power produced by water with its cost produced in the same market by steam if some competitor should build a steam plant there.

The cost of water power in general is rising on account of the increasing cost of labor due to shorter hours in the form of three instead of two shifts and higher wages, the increasing cost of materials, and the generally increasing taxation, employers' liability and similar items of expense that are characteristic of industrial operations in the United States. In spite of all these circumstances and in spite of a steady rise in the cost of coal, the cost of steam power is steadily falling.

At equal cost the scales of the consumer's choice almost invariably turn against a water power and decide in favor of steam power because, among other reasons, it is generated in the market where it is consumed, whereas water power has to be brought from a distance and suffers the risks of a long transmission line. Also steam power is more flexible and is free from the influence of dry seasons or floods. Water power must be considerably the cheaper before it can compete.

The increasing introduction of steam power, devouring our coal fields at a time when millions of horse power of water power are undeveloped, is a crime against the policy of conservation. Each new steam plant is an agency devoted in effect to the perpetual consumption of coal, and coal is a limited commodity. While absolutely essential for smelting and practically essential for the heating of our houses, it is not essential for the production of power.

Steam power is consumed only when it is used; water power whether it is used or not. If the power of a water fall is not brought to the neighboring city to turn its wheels, do its cooking, or light its lights, the power is developed just the same at the falls and expresses itself in grinding the rocks at the bottom and the heating of the agitated water. Postponement of coal consumption would be real conservation. Postponement of water power development is real waste.

If water power, instead of being at a disadvantage compared to steam power, were fully its equal as to cost of power delivered and certainty of operation, it would still be at a serious disadvantage when construction is under consideration for an added reason which aggravates the whole relation of water power to capital. This is the excessive capital required for a water power as compared to that required for a steam power of the same capacity.

A typical modern steam electric station, including real estate and every other item of cost up to the distribution system, can be built for $45 per switchboard horse power of output. A correspondingly typical hydroelectric development of the same capacity, for moderate head, including transmission lines and substation, would cost in the neighborhood of $135 per switchboard horse power of output, which figures are in the ratio of 1 to 3.

Capital for a steam-electric station is relatively easy to raise. The natural hazards are considerably less. The property is concentrated under one roof, instead of being distributed over many miles of country. There are no actual or threatened adverse laws to introduce doubt as to the security of investment. Popular prejudices are more likely to favor rather than to be against the economics of a steam station. Large supplies of coal are seen going into it and the public appreciates these must be paid for. The plant, to the popular eye, seems to be hot and busy and entitled to its rewards. In the case of the water power, for reasons that have been mentioned, capital is more difficult to raise, and besides being more difficult to raise, three times the amount is required. It is not difficult to see why, at equal cost of power delivered if it is a question of building a steam or a water power, the steam power gets the preference, and when, as is increasingly the case east of the Mississippi, the cost of a horse power-hour developed by steam is so much less than when developed by water, the "water power situation" is removed from the court of discussion before a decision is reached, because of the fatal competition of steam.

It may be asked—will the cost of steam power continue to decline, notwithstanding the continued rise in the cost of coal? There seems every reason to expect that it will, for with the best plants of today, improved as they are, the return from a pound of coal is only 17 per cent of the power it contains. Internal combustion engines operated by liquid fuel have not yet cut much figure as large sources of prime mover power, but they are constantly undergoing improvement. In the generation of steam, where boiler pressures of 150 lb. were used a few years ago 275 lb. is now used, and higher pressures up to 400 lb. are under experiment, together with higher degrees of superheat than the past has thought possible, and it is not too much to expect considerable improvement in steam economies from progress already in sight. There is also much latent possibility in the gas turbine. In view of all this, he would be rash who notwithstanding the steady moderate increase in the cost of coal would predict an increase in the cost of steam power.

While the cost of steam power has fallen and is falling, due largely to an increasing efficiency in the conversion of heat into power, and while this efficiency is still so low as to render further increases not only possible but probable, the efficiency of water powers has practically reached its maximum and further reduction in the cost of water power from improvement in efficiency is barred. Reference will later be made to the only direction in which substantial reduction is possible.

The unfortunate necessity of relatively excessive capital throws difficulties into the path of water power in more ways than one. Not only is excessive capital required before the development can be created, but after it is created there is a handicap in the magnitude of the bond interest constituting the principal element of cost of operation—using this term in its broadest sense. Both by the large investment of capital required and the large return to capital appearing in its cost of operation, water power development is led conspicuously into the realm of the relations of wealth and capital to industry and the social system, which relations are subjects of keen political and economic controversy. The water power problem, being exceptionally dependent upon capital, is the innocent bystander that suffers from the quarrel between two struggling antagonists, both of whom its development would enormously benefit. A unit analysis of the gross operating expenses—using the term as before, in its broader sense—of the typical steam-electric and hydroelectric system I have referred to may be of interest, and is given below for annual load factors in both cases of 50 per cent and coal at $3.25 per ton, delivered.

UNIT ANALYSIS OF GROSS OPERATING EXPENSES IN TYPICAL STEAM-ELECTRIC AND HYDRO-ELECTRIC STATION OF THE SAME CAPACITY, 20,000 H.P., ANNUAL LOAD FACTOR 50 PER CENT, AND PRODUCING POWER AT THE SAME COST. COAL $3.25 PER TON DELIVERED. RETURNS TO CAPITAL 7%

	Steam station per cent of total gross operating expenses	Hydroelectric station per cent of total gross operating expenses
Administration	4.0	4.0
Ordinary operating expenses (except coal)	10.6	4.8
Coal	48.9	....
Taxes and Insurance	6.7	2.8
Depreciation	10.8	11.0
Bond Interest	19.0	77.4
Total	100.	100.

As will be seen from the table, bond interest is the largest hydroelectric expense. In the typical case considered it constitutes 77.4 per cent of the total operating expenses. In the steam station it is only 19 per cent.

The largest expense in the steam station is coal, amounting to 49 per cent of the total. This everyone can understand and nobody begrudges; but there is a small body of opinion which considers all interest usury and to this group the fact that over three-fourths of the cost of producing power in a water power plant represents interest is almost equivalent to saying that the cost of water power ought to be reduced by three-quarters. The whole cost for coal in the steam station is only two-thirds of the cost for interest in the water power.

The classification of bond interest in each case under the head of operating expenses is not customary, but is done for the purpose of giving a clear conception of the radical difference between the compulsory items of expense in the two types of stations.

There is a tendency in many quarters to regard bond interest as profits. This is fundamentally erroneous. It is comparable to regarding the rent a grocer pays for his store as profits. His profits do not begin until after the rent is paid under penalty of eviction, and similarly the profits of a water power do not begin until after the bond interest, which is rent for the borrowed money, has been paid under similar penalty of eviction by the foreclosure of the mortgage. The holders of the bonds have no interest in the profits of the development. Their returns are set by the prevailing rate of interest in the bond market, and not by the prosperity of the enterprise. They get their returns, in theory at least, whether there are profits or not. It is true that bond interest is sometimes in default, but the holders have the right to take possession of the pledged property, foreclosing and recouping themselves out of the proceeds of its sale for both principal and defaulted interest. It is partly by regarding bond interest as profit that the impression that water powers are very profitable has gained acceptance.

It is natural for a spectator surveying a hydroelectric development to gain the impression that the power comes from the water, which, costing nothing, should render the power cheap. It is evident to a spectator that outside of bond interest the operating expenses of a water power are relatively very low, being in our typical case only 22.5 per cent of the total, which includes ample allowance for depreciation, taxes and insurance. But so much of a dam is in hidden foundations and in parts under water and so much of the long transmission line, rights-of-way and power house and substations is out of view to a spectator, that even though he be liberally inclined towards the deserts of capital, he constantly underestimates the amount of capital invested and neglects to include in his conception of the cost of the power, adequate charges for the service of this capital.

Business men know that profits depend not only upon excess of price over cost of product, but on " turn-over— ", which is the ratio of aggregate sales to capital.

If we compare a steam-electric with a hydroelectric power of the same capacity in both of which the selling price of a horse power-hour is the same, we must permit out of this selling price a greater proportion of gross profit in the hydroelectric or we cannot yield the same return to capital, since there is three times the capital to be served. In other words, there is only one-third of the "turn-over". The activity of capital in a hydroelectric plant is very low, much lower than in a steam station, and much lower than in almost all other branches of industry such as manufacturing.

Certain public service commissions have hampered water powers by not recognizing the distinction between bond interest as a compulsory expense paid as the rent for money loaned, and dividends as an earned reward for the risk of the business and skill in management. They have in effect ruled that the total return for bond interest and dividends together must be limited to a certain amount—eight per cent in the recent decisions in California. The result of this in attempting to secure new capital at a time when bond interest rates are tending to rise is going to be the same as if a grocer, when his rent is raised because of improvement in the opportunities of the neighborhood, should be ordered to accept smaller profits in order to keep the total of his rent and profits the same as before. If he were free, he would decline to do business under such conditions, and if not free his plight would be a warning to others.

There has been considerable discussion about the length of term for a permit or franchise after which recapture clauses can take effect, and those interested in water power are not agreed seemingly because of difference in approach to the problem rather than difference in conviction as to the effect of certain provisions.

For a simple water power unrelated to others and not expected to grow, a fifty-year term might at first sight seem long enough to remove from influencing the raising of capital, discussions concerning the favorable or unfavorable developments final to the term. Those who are less concerned over final conditions are often, although sometimes unconsciously, relying upon the extreme improbability of the exercise of the right of recapture, with such loss as it might involve.

But ten years of the fifty would often run between the granting of a permit and the time a bond issue was put out and construction commenced, and three years more would often run before operation began, so that the recapture conditions might indeed come within the life of a forty-year bond and have a sentimental, if no other, effect upon its acceptability and price.

But growth is a characteristic of successfully located and successfully managed water powers, and ten years after the completion of construction perhaps the development of a second location further up stream by the same company becomes desirable. While a fifty-year permit for the new development may have no disadvantages, the new bonds of the company must take into view the approaching expiration of the permit on the first development, which now is only 27 years off, and by the time a three-year period of construction of the second development is completed, will be only 24 years off.

We now reach a time when it becomes of the highest importance to know just what the conditions and effect of recapture will be. If we are successfully to solicit capital for our new venture and if we are to continue to be able to invite industries to locate and develop in our territory, building extensive factories and communities in the security of long-term power contracts, the possible recapture of the original development must contemplate taking over not only the dam site, which is all certain proposed laws have included, but the transmission lines, substations, steam auxiliaries and all appurtenances and adjuncts that make the development an operating whole. The existing power contracts and all other contractual obligations of the development should also be part of the obligation of recapture.

In default of this the application for new capital will be unsuccessful, because there will be feared a limitation of opportunity and a disorganization of the management, possible liability for unfulfilled contracts and possible loss from recapture at a depreciated physical, instead of a fair, value.

If recapture is to be on terms involving a known definite loss—in several bills reversion of dam and power house without compensation has been proposed—an appropriate sinking fund must be set up to offset this. Suppose such a sinking fund to be one per cent of the cost of the original development and to be set up thirty years in advance of the expiration of the permit. This 1 per cent expense seems small; but if we consider that the total return on the cash cost is not likely to average over 10 per cent, of which, for purpose of illustration, 7 per cent may be regarded as bond interest and 3 per cent as profits, the 1 per cent sinking fund for the amortization of the loss of recapture would absorb one-third of the profits of those owning the equity in the venture and bearing the risks and earning the rewards of management.

Reference has been made in only a general way to term of permit and conditions of recapture in illustration of the kind of problems these questions throw into the path of promoters and engineers seeking to make water powers attractive to capital.

A number of their chief impediments are removed and water powers take on a new aspect when viewed as a source of secondary power in addition to their primary power. Capital for a given output greatly diminishes, market is rendered more stable, transmission lines are cheapened, since industries that use secondary power can locate near the development, and the cost of such secondary power manifests itself so low as to help to restore the effective competition of water with steam. In many cases secondary water power would be so much cheaper than steam that impetus would be given to the creation of industries and industrial processes now dormant because the cheapest steam power is too expensive. For process purposes, continuous or primary power is not necessarily required, and advantage can be taken in large numbers of cases of the enormous amounts of water power in excess of minimum flow or of partly equalized flow now wasted in other than the dry seasons. If by wise provision we can nourish our struggling water powers with the increased revenue which, generally speaking and without interfering with primary power, secondary power could yield, the total cost of both services would be so greatly reduced that water powers would again in a large number of cases assume the place they held before steam power became so cheap, and, east of the Mississippi, began to rob them of their birth-right. The water powers would then be able to conserve coal, up-build communities by cheap power, and encourage location in this country of industries that now go elsewhere.

If, in addition, the attitude of the public, and in harmony with it the attitude of the public service commissions and of the government should change toward water powers so as to regard them as friends, capital would again flow liberally and the public, the government, the capitalists, the promoters and the engineers would all be highly benefited and rewarded.

But even independently of the cultivation of secondary power a great deal can be done to develop our water powers as they are, especially west of the Mississippi where three-quarters of the water power resources lie, and where, generally speaking, on account of the high cost of coal, water power is normally cheaper than steam power. While for the time being the Pacific states and some of the mountain states seem to be over-developed in respect to water powers,—lacking market, rather than development—there are numerous specific cases where development is urgently needed but deterred by the considerations that have been mentioned. Power consumption per capita in the United States is increasing so rapidly that unless we wish to shut our eyes to the staggering rate at which we are making inroads upon our exhaustible coal supplies, the development of our water powers is imperative.

The West needs them to get power more cheaply than is afforded by the relatively high-priced coal and oil, and with this cheaper power it can in time work wonders in industrial and agricultural development. The East needs them as a source of power cheaper still than the already cheap steam power and as a substitute for the fuel-produced power that is eating out the vitals of our fuel resources, which should be conserved for purposes that only fuel can serve.

The "water power situation" is costing the country many millions annually in actual loss and in retardation of industrial development.

It has been shown that reduction in the cost of water power cannot be expected from further inventions or improvements in the art of engineering, but nevertheless the cost of water power is susceptible of considerable reduction from improvements in another direction.

In our typical case 77.4 per cent of the cost of production of a horse power-hour was composed of bond interest. The table was compiled on the assumption that money was worth seven per cent for water power purposes. If its owners could be induced to lend it for five per cent the bond interest would be reduced by 28 per cent and the cost of production of a horse power-hour by 22 per cent—a reduction important enough in many cases to turn the scales against steam power and result in the bringing of a new water power into existence.

Or if the case occured in the West, a 22 per cent reduction in power cost would go a long way towards encouraging the use of power for purposes previously out of its range.

A five per cent bond interest for the typical case is not visionary. Railroads enjoy it and many industrials.

Water powers could enjoy it if there were a change of policy towards them on the part of the public, the commissions and the government that would make investments in them secure, remove all but the property taxes they now bear, eliminate the many extra construction costs, expenses, delays, technicalities and injurious limitations they suffer, and bring them to a position of being, under the fostering care of the government, a boon to the public.

The writer, for one, thinks this change will slowly come. It has already started. Little by little the interests of the parties to the controversies are being discovered to be identical. Little by little publicity and the pure light of intelligence will permit economic laws to have their free play and the "water power situation" will disappear, giving place to a rapid development that will benefit our citizens as consumers, strengthen old and develop new industries and save our coal, putting us in a superior position not only with respect to power but in respect to the influence power is having upon the development of all the resources of the country.

DISCUSSION ON "WATER POWER AND DEFENSE" (WHITNEY), "THE WATER POWER SITUATION, INCLUDING ITS FINANCIAL ASPECT" (DUNN), WASHINGTON, D. C., April 26, 1916.

F. A. Lidbury: I am glad this question has been brought up, because there has been for years a tendency on the part of electrical engineers in connection with their valley load problems to assume that the electrochemical industries can offer an easy solution. The tendency appears in various ways. There is the steam central station man who comes to electrochemical manufacturers and says, "We can offer you lots of power at cheap rates if you will only take it for a few hours of the day." When you find out what he means by cheap rates you get a shock; but putting that aside, and putting aside the fact that few electrochemical processes can operate satisfactorily in an intermittent manner, let us see what he is trying to do. He is trying to relieve his prospective customer of the investment portion of the cost of the steam power. What is forgotten is that he is asking the customer to increase his own investment charges.

Putting all other considerations aside, let us see how that works out. The consensus of opinion as shown by the figures given today is that the cost of steam plants may be taken as something like $60 per kw. capacity. I venture to say—and I have consulted some of my electrochemical friends present who confirm the statement—that there is not an electrochemical plant in the country that does not involve an investment of at least $50 per kw. in plant cost. Many electrochemical plants run to several times that figure, and the average would be much higher, and might be two or three times as high. What the central station man is asking is therefore that his customer should increase his investment charges to an extent usually considerably greater than those of which he is being relieved. Intermittent operation is in some cases not possible, in others at least inconvenient; but the fundamental reason why these industries do not gobble up the off-peak of steam central stations is the one just given.

Then there is the question why electrochemical industries do not flock around those water powers which have valley power or secondary power at—in this case actually—relatively cheap rates. The answer is again that the added investment cost, taken in conjunction with disadvantages of intermittent operation, is such as to more than neutralize the advantage of the lower power rate. Partial time operation of electrochemical plants does not therefore offer much hope as a solution of these problems. I am not saying that there are not times when it can be done, but I am speaking now of normal conditions.

From the electrochemical point of view the figures given in Mr. Dunn's paper would require modification. His comparisons between the cost of power from steam and hydroelectric installations, on the basis of a 50 per cent load factor, would be very different on the basis of a 100 per cent load factor. It is obvious from a consideration of the figures Mr. Stillwell gave this afternoon that water power costs become relatively more favorable than steam power costs as the load factor increases, and vice versa; and, as Mr. Stott pointed out this afternoon, there is under every set of conditions a point where the two curves cross. The load factor of electrochemical plants usually lies well above that point.

There is one corollary which is not usually drawn as clearly as it should be. Mr. Dunn mentioned some of the favorite legislative prescriptions put into bills in connection with water power. One of the most ridiculous of these, which occurs in almost every bill relating to water power, is a provision that preference in the distribution of such power shall be given to municipal and similar purposes. In other words, you must provide the type of power which is most costly to develop with those particular loads which have the worst load factor. It has been sufficiently pointed out today that for that kind of load, even under the most favorable water power conditions, a steam plant will do the work cheaper and better, and it is about time that we got it out of the heads of legislators that the proper, decent and reasonable thing to do is to tie a water power plant preferably to those loads of the worst possible load factor.

In connection with legislation one or two other points must be considered. There is the question of taxation of water power to which Mr. Dunn referred. It has been clearly pointed out, principally in Dr. Whitney's paper, that for certain electrochemical processes, particularly for the fixation of nitrogen, we have got to have power at much cheaper rates than at present in order to permit their development. Specific taxation of water power is not likely to lead in this direction; it simply makes it more difficult to introduce industries which the country vitally needs.

Next, as regards the provision that water power plants shall revert to the government, say at the end of 50 years. What about the consumptive industries that have sprung up around such water powers? In most cases where artificial restraints are not put upon distribution, these will largely be electrochemical plants. These plants will be useless except in connection with the water power plants, and they will be providing supplies of fundamental importance to the general industries of the country. The investment involved in these electrochemical plants will be at least as great as, probably considerably greater than the investment involved in the water power plant itself. That is a matter which should receive very careful consideration —what is going to happen to these plants, to the investment they represent, and to the industries which have become dependent on their products, if by some carelessly drawn reversion clause they are liable to be thrown on the scrap heap at the end of 50 years?

Most of these points are more or less related to the strictly electrochemical side of the question; but I feel very strongly that either the future of most of the water powers in this country will be bound up with electrochemical industries, or there will be no future at all for them.

Lawrence Addicks: What Mr. Dunn says about seasonal variation puts a little different color on this question of off-peak power. I have been thinking of diurnal variation, and I think Mr. Lidbury was in what he said, as I certainly was in connection with what I said this afternoon. If you put to us the proposition what we shall do in the ten months of the year, our first question is—what do you mean by cheap power? Do you mean $10 per h.p. year or anywhere near that figure?

Gano Dunn: That or better.

Lawrence Addicks: What will we do with large quantities of power at $10 per h.p. per year, ten months a year, and nothing for the rest of the time? That requires a business which could be carried on by using the current for a part of the time, and working up the product in other ways the rest of the time, and in the few minutes I have had to consider the matter, I can not think of any case where it looks inviting. In order to comply with the proposition it means that we must use so much power in the business that the cost of the power is the main thing, and we will do anything to get cheap power and shut down the business for two months in the year, during that time paying fixed expenses and salaries.

One of the industries in which such a proposition might be considered is the nitrogen industry by the arc process, and I think it would be a very interesting thing to consider. We are now trying to get the government to consider this manufacture of nitric acid from the air, and we are talking of subsidizing the industry, and if Mr. Dunn will come forward with a proposition which will yield very cheap power ten months in the year, it would be worth considering. The arc process uses about 25,000 kw. per ton of 100 per cent nitric acid. The aluminum industry is another which might be considered in this connection.

John H. Finney: The answer to Mr. Addick's question in connection with the aluminum business is perhaps best found in the fact that we are building today something over 150,000 h.p. in hydroelectric power for the manufacture of aluminum, to work twenty-four hours a day, and 365 days in a year. I do not believe secondary power, even for ten months, would interest an organization such as ours.

I should like to comment briefly on Mr. Dunn's paper. The electrical engineer is essentially an optimist. That may not be apparent from the papers read today, and from some of the discussions, but if he were not an optimist, I do not think he would be found here today talking water power. If he were not an optimist, he would be, by this time, thoroughly discouraged by the stagnation that has existed for the last eight or ten years in the water power business. If he were not an optimist he would not still be trying to "unlock" as President Wilson puts it, this great natural resource and this tremendous, though latent, asset towards industrial advancement and preparedness.

The purpose of the meeting of the American Institute of Electrical Engineers and of its Water Power Committee here today was to call attention to a phase of hydroelectric development that seemingly has not had much thought by legislators and department officials who deal with this question.

We thought it might be helpful to stress the important uses to which water power can be put by the electrochemical and similar industries. Congress has in mind the value of water power measured by its public utility use solely, and the vast majority of the water powers of the United States are not in that class and never will be, in my opinion.

The great bulk of the water power in the United States is only available for what might be termed a semi-public use—a so-called private use, it might be, of the electrochemical industries, the semi-public use of power for pumping water on to arid lands; serving as motive power in the electrification of steam railroads; in making fertilizers, or in making nitrates for explosives. These are not, strictly speaking, public utility uses, but are much broader, much more important, in that the energy creates not incandescent lighting for instance, but the vastly more valuable products embraced in increased transportation, or increased agricultural production or new and cheapened products of the electric furnace or electric bath.

The public utility use of water power is mainly that of using it as a part of the combined water and steam generating system and therefore it might be no particular hardship to the public service company to have a given water power taken away from it at the end of a fifty year period, because they could at that time substitute a steam plant, or perhaps another water power plant if it were in reaching distance of their operations, but the great mass of these chemical operations, this irrigation work, this electrification of steam railways, requires, first, *cheap* power and secondly and just as importantly, it requires *permanent* power. These operations require power in perpetuity, and that is another thing that our Congressional friends do not seem to have in mind, *viz.* the difference between permanent use, and permanent rights. Great works of the expensive and permanent character required for the development of water power cannot be financed with the expectation or suggestion that they must be abandoned at the end of a fifty year period, or that money invested in them is subject to suspicion and to grave risk of confiscation in whole or in part.

Permanent works are built to supply a permanent use which so far as we can now see will always be performed in the same way—whether the original lessee continues to perform it or another lessee or the Government finally performs it, does not greatly matter, it seems to me, so long as it is proposed to deal fairly and equitably with the original lessee. Cheap water power in the United States is only possible with cheap money to build water power plants—every unnecessary property restriction causes dear money and more costly power, and materially limits the available water power resources of the nation, as has been well pointed out by Mr. Dunn and others.

If the Institute can bring about a better understanding of what these industries mean in their importance to the nation, we have felt that we would be doing ourselves credit as leaders in the electrical arts, and we would be doing the nation a service, by pointing out what we consider fundamental engineering principles and fundamental economic principles, without the recognition of which no permanent water power policy can be written by the Congress that will bring about that wide development so necessary to the industrial growth of the nation.

L. H. Baekeland: Mr. Gano Dunn referred to some statements I made this afternoon on the subject of wasteful banking. I would like to explain what I meant. Before doing so, I want to answer the remark Mr. Finney just made. He asked: "What is the real importance of some of these electrochemical industries? I could take, for instance, the manufacture of nitrogen-fertilizer which requires such very cheap power, and for which the market is almost unlimited if it can be supplied at a sufficiently low cost. In all our discussions we have been rather indefinite as to what we mean by cheap power. For instance, in the city of Yonkers, I am charged 12 cents a kilowatt hour for current. I think that is cheap, because I cannot do any better, and furthermore, the matter of annual expense in this case amounts to little. So I do not mind much the 12 cents a kilowatt hour they are charging me. I am kicking more about the ugly poles with which they are butchering the landscape and defacing my property, and I would gladly pay 15 cents per kilowatt hour and call it cheap if the company did not put its horrible poles in such inappropriate places.

But when we speak of cheap power for fertilizers we mean $4 or $5 per horse power-year, twenty-four hours a day continuous service. Why do we want cheap fertilizers in the United States? I was born in a country where farm labor is unusually inexpensive, and I know, therefore, that there is hardly any comparison possible between cost of farm labor in Flanders and that in the United States. In Flanders, farm labor is mostly a family affair. The peasant, his wife and children work in the fields, and they feel happy in doing so. They receive no wages; they work practically for their board, and even that does not amount to much.

When farmers, at such low rates of labor, find it profitable to utilize cheap nitrogen fertilizers—and after all fertilizer is a labor-saving device—when we see again that in this country, where farm labor is incomparably more expensive, we cannot

Vol. 35
1916

afford to use cheap nitrogen fertilizer, because it costs twice as much as in Belgium or Germany, then "there is something rotten in the State of Denmark."

We can produce very cheap nitrogen fertilizer by fixing the nitrogen from the air if we have cheap power. The chemical processes to do this are well known and the sources of cheap power are here too. But for several reasons, by the time we develop the power, it has become too expensive for profitable use with these processes. Some of these reasons have been well put forth by Mr. Gano Dunn, and what I am telling you now is not in opposition to his statements. Right here is where our wasteful banking comes into play.

When twenty-seven years ago, I landed in this country, one of the first things which struck me was that most commodities here are cheap enough at their source of production, but they are tremendously more expensive by the time they reach the consumer. If I were to put it in another way, I would say that one of the curses of this country is the unnecessary multiplication of middlemen, and this situation goes against the grain of engineers or chemists who work for efficiency. Sometimes I think we are a lot of fools when we work and put forth our best skill, our best efforts, striving to increase efficiency in power production or in chemical processes so as to decrease the cost one cent, or a fraction of a cent, or to reduce power consumption a few per cent and then, after we are all through with our improvements, our increased efficiency looks like a mere trifle if we compare it with the big gap of waste which has to be bridged between the producer and the consumer.

Now in regard to water powers: Take, for instance, a suitable water-power site, including real estate and water rights. An engineer comes along and sees the possibilities of the situation for water power development. Almost immediately he is confronted with some real estate speculation in which some men have to get rich. The next step is the advent of the promoter who wants to get rich too, and most of the time very quickly. Then comes the banker and the bond-broker, and then finally the water power enterprise gets to the point where the equipment gets into the hands of a manager, and the power is now available to the consumer, who finally finds that it is too expensive for him to use it, because at each step in its development, the fixed charges have been increasing. That will not do for cheap power. Cheap powers in Norway, or other places abroad, are not burdened by those extraordinary fixed charges which were incurred by having to go through all these middlemen. Whenever one set of financiers or underwriters control the whole enterprise from the inception of the water power to the construction of the chemical works and the delivery of the final manufactured product to the consumer, it stands to reason that the final cost of the water power will be cheaper. In some cases here in the United States, I found that the cost of operating water power represents only 10 per cent of the fixed charges introduced by banking or financing, so that any important reduction of the cost has to be found more in the financial end than in the engineering or operating part of the proposition.

Now, what would you say, for instance, if you started to manufacture sulphuric acid, and if first of all your plant is located on a piece of leased ground where you are compelled to pay such an exorbitant rent because the people who possess the real estate have to get rich by it, and then when you purchase your raw materials, another set of people have to levy considerable profit on this, while you, as a manufacturer, would have to get your share in the manufacturing operations after being confronted then again with a selling agency which would claim high commissions, until finally the product, after getting through the hands of all those middlemen, comes in the hands of the consumer at a greatly increased cost. The up-to-date sulphuric acid manufacturer, in order to make a success of his enterprise, begins by owning land or real estate, and he secures his raw materials directly, and when it comes to selling, he does not have to go through the additional expense of middlemen. Therefore, he can afford to deliver his sulphuric acid at a minimum cost. Somehow, we have not yet reached that point in the utilization of our water powers. It is true that in some cases, none of the intermediaries get very much separately, but in the end, they all get something, and these expenses are multiplied collectively until they sum up to a considerable increase in the cost of power, and that is the reason why our water powers are generally so much more expensive than they are in some other countries.

The remarks of Mr. Dunn are correct, that our capricious and ill-digested methods of legislation on the subject of water powers have not contributed to make enterprises of the kind more inviting, and this has raised the rates of interest at which money could be borrowed for this class of enterprise.

On the other hand, we are told that in Germany or some other European countries, there is no opposition between private enterprises and the government, such as has existed of late in this country. I should point out that this matter was disposed of by the very fact that in many instances, the German government has run these public service enterprises as a monopoly or has become a partner in them. For instance, there is no struggle between railroad companies in Germany and the German government for the reason that the German government owns and runs the railroads.

A short time ago, in studying the taxation system of Germany, I found that the earnings of the government railroads paid about 40 per cent of the total expenditures of the German government, and the general taxes of the country are reduced by this amount. In other cases of public service enterprises, like mines, etc., the government became an important partner in the enterprise, and in this way, succeeded in controlling easily these enterprises from within, instead of trying to curb them by drastic legislation from without.

I do not say that we should copy these methods. I merely want to point out where we are laboring under difficulties which might be removed if some way could be devised by which the government could enter into efficient cooperation with these enterprises. Some of the privately owned public enterprises in this country, I am sorry to say, have not always been carried out in the interest of the stockholders who had invested their money in these properties, and this too is a very important reason why capital has become shy and wants increased interest rates so as to make up for any contingencies of failure aside from fear of disturbing legislation. This undoubtedly has raised the fixed interest charges for any similar enterprises which might have to be launched.

In England, canals which once were privately owned, were subsequently bought up by railroads and they proceeded to take great care that the canals could not be used in competition with the privately owned railroad enterprises. In this country, we have become so "socialistic" as to have canals which belong to the state. I understand that in Germany, all the canals are owned by the government, and I know that they are kept in the most splendid condition of efficiency and the government can afford to maintain and improve them even if such action is in direct competition to the operation of its own railroads.

In general, there is a great difference in efficiency in any country when enterprises or the details of government are run by engineers and experts instead of by politicians.

Mr. Gano Dunn, a year ago, in this city of Washington, advanced the idea that an engineer should never mix in matters of government administration. I told him at that time, that I disagreed with him. Then after his interesting paper today, I disagree still more, because he has proved by his own example the versatility of our engineers.

We are encountering quite some difficulty in the problems of government of this nation. But we should not be too impatient. These matters are straightening themselves steadily—only a pessimist can deny this. We are confronted in this country with entirely new problems which have to be treated in new ways. These problems are considerably complicated by the immense and rapid growth of our Republic. The fact is that this country, as it grows larger and larger cannot keep on being run in the easy-going ways of a mining camp. We have come to a point where we have to change our methods, and in this we have to do some experimenting, just as we are doing in our chemical industries. If it were not for direct experimenting, our chemical industries could never have made progress. We are very lucky if, only once in awhile, some of those experiments are successful, and we do not count so much the ones which have been unsuccessful as long as we make headway. These problems cannot be solved by a general formula, inflexible and everlasting. Furthermore, whenever we discuss these problems, we are apt to be carried away by one single point of view or another and on this account, we frequently exaggerate one single feature by looking at it from one standpoint. This is the mistake of most of our politicians. When we talk about these matters, let us discuss them like engineers. Let us use quantitative argumentation and let us impress those of our friends in Congress or the Senate who are really willing to learn that we, at least, can look at the situation with a due sense of proportion by using quantitative arguments and not be overawed by merely qualitative considerations.

C. G. Atwater: The point I want to discuss is contained in the first sentence of the summary in Mr. Whitney's paper, namely, that the United States has no adequate source of fixed nitrogen. I think that point is open to some question. Further along the paper makes an exception of the gas and coke industry.

I presume that Mr. Whitney in writing the paper did not consider the dimensions of these industries nor the present conditions that prevail in them. As a matter of fact, so far from there being no source of fixed nitrogen, there is being produced every year in this country from the carbonization of coal to make coke about 750,000 tons of sulphate of ammonia, or equivalent to that. That figures up pretty nearly to our whole consumption of fixed nitrogen. It is not all being recovered, but it is a source known to be open for the recovery of that amount. There is at present being recovered of that amount about 220,000 tons of sulphate of ammonia per year.

That is a very fair proportion, but it is being largely increased. The development of the coking industry that has come with the present abnormal conditions, though largely from the natural growth of the iron and steel business, has brought about very nearly the doubling of that industry, potentially, within the last few months; that is to say, contracts have been let for some 2600 coking ovens which will produce about 150,000 tons of sulphate of ammonia per year.

Now, as you will see, that is very far from the country being in a position of having no adequate source of fixed nitrogen.

I do not wish to make these suggestions from the point of view of checking or discouraging water power development, but when you come to figure these things out and deal with our friends the bankers and others, these points will have to be considered.

There is a tremendous increase under way in the by-product coke ovens, as I have said, and it will amount to more than I have stated, because I have only referred to ovens actually under contract. There are 2000 or 3000 more under consideration. The business of recovering the by-products wasted in coal is being rapidly developed to somewhere near the position which it should occupy. That is also being applied to the recovery of nitric acid. It will be possible to convert ammonia from coke ovens into nitric acid. There is no question also that the development of the coke ovens will contribute toluol and other substances essential in time of war.

Calvert Townley: I had an opportunity some fifteen months ago of visiting the nitrate pampas of Chile and of inspecting the methods used for getting out this valuable product. It may interest you if I say, that I was impressed with the possibility of very greatly cheapening that product to the ultimate consumer.

We must remember that for a long term of years the Chilean nitrates practically had a monopoly, that is to say, the output of Chilean nitrates so largely exceeded that of any other similar products that the competition of such products was unimportant. The nitrate earth of Chile was very rich and to work it was very profitable, no matter how inefficient might be the methods of extracting the nitrate, consequently the processes were crude in many respects, and the operators did not seek for the economies which might have been practised if the pressure of competition had been severe. I am not a chemist but it was apparent even to me, as it would have been to any engineer, that there were possibilities of material improvement in the economy of the production of nitrate.

When I was there, owing to the European war the industry was prostrate. Only about 30 per cent of the plants in the country were in operation, and these were running on part time only. Some 30,000 laborers had been thrown out of employment, and I never saw a more discouraged and disheartened set of men than the operating officials who had to do with this industry. They did not know what was going to happen next. One thing which had happened was that they were studying to improve processes for the extraction of nitrate, and it is usually a safe prediction that when a body of men who have been interested in an industry for a long time have sufficient incentive to make improvements they will make them provided there is any considerable margin to work on.

Before the war the Chilean government received some 60 per cent of its annual revenues from export duty on this nitrate which amounted, in round figures, to about $11 a ton. It is an arbitrary duty which of course can be changed, and because the industry was then almost prostrate the question of modifying this duty was being discussed. If artificial processes for getting fixed nitrogen should be established on a scale large enough to jeopardize the Chilean industry it is only a fair prediction that the Chilean government will reduce its export duty.

There is still a third direction from which a reduction in the cost of nitrate may come. The cost of transportation—bringing the Chilean nitrates from the pampas where are the mines and reduction mills to the American market, has been abnormally high. None of the reasons for this fact are fundamental; they are all more or less the result of monopoly or of limited facilities and the cost is consequently subject to future reduction should the transportation agencies be improved or competition become severe.

The very live possibility that our country may become involved in war and the pressing need of providing for such a contingency should not blind us to the fact that we have lived many years at peace with the world and are likely to so continue —therefore no plan for producing nitrogen will be economically sound which is not commercially practicable under peace conditions. While the quantity of nitrate in Chile has been seriously depleted it is still sufficient to supply the world for years to come and its early exhaustion can therefore by no means be counted upon. This means that any cost for power which we may now estimate to be low enough to permit the artificial fixation of nitrogen in competition with the natural salts, may have to be radically revised downward later on. That furnishes another reason why we must make every possible effort to cut down our power costs. On the other hand, of course all of the processes for the fixation of nitrogen as now known are relatively new and susceptible of much improvement. I understand that not more than 15 or 20 per cent of the electrical energy required by the arc process is actually used in the fixation of nitrogen. Perhaps some of my chemical friends will correct me if I am wrong.

L. H. Baekeland: It is 2.5 per cent.

Calvert Townley: Well, it is worse than I thought it was. That being the case, is it not fair to assume that with the brilliant minds which are at work on this problem a great improvement is likely to result? May we not hope that the processes will be so improved that the industry can prosper with very much greater power costs? A process with an efficiency of 2.5 per cent which could live and pay $7.50 per h.p. per year could presumably do quite as well with a $22.50 h.p. if the efficiency could be raised to 7.5 per cent. One way to have the processes improved is to get people into the business. We all know that there is no teacher like experience, that necessity is the mother of invention, and that if we can get not one, but a dozen, or fifteen, or twenty, or even a hundred corporations interested and competing with the hope of ultimate profit, such competition will bring out the best efforts of the brightest minds. The result will be that in this industry, as it has been in every other industry with which electricity has been connected, the efficiency will rise and costs will go down, making it possible to use power at a cost which now is entirely out of the question.

Those are to my mind important reasons why we should set ourselves earnestly to the task of getting this industry on a basis where it can go ahead.

One thing very clearly shown in Mr. Dunn's paper, is how large a part the cost of capital plays in a hydroelectric enterprise. No engineer could fulfill his obligation to his client without considering the question of the security of any investment. Technical matters can occupy but an insignificant and minor position if there is a risk that the entire sum put into an enterprise, or any part of it, may be forfeited.

Capital conveys to many minds quite an erroneous notion. We are apt to think of it as something entirely separate and apart from ourselves. We think of a banker as a man who himself puts his own money into enterprises. Now that assumption is fundamentally wrong. Investors are not the bankers, they are the men in this room. They are all of us, and our friends. To be sure we do not individually build water or steam power plants for the very obvious reason that such enterprises require large sums of money and there must be some one who will undertake to find out whether or not an enterprise is right and sound and then get the necessary funds together for the undertaking. That is just what the banker does. He is a sort of Captain of Money. He scrutinizes an enterprise and agrees to or refuses to back it, not because he himself likes it, or because he does not like it but because he knows the sort of investments which his clients, you and I and our friends, are likely to put money into.

Some one said something here this afternoon rather critically about the lack of patriotism in capital. Now, capital is a commodity just like grain, or cattle or clothing. It can be obtained for a price and it goes where it can find the best market. Not one of us would stand silent, accused of lack of patriotism, but who is there here who would put his own savings into an unprofitable or an unsafe enterprise to help develop water powers in the west when he might invest it profitably somewhere else? To rail at the man with money because he will not let us have it at a lower rate than he can get elsewhere is just as unreasonable as to demand that our grocer sell us eggs at 30 cents per dozen when he can get 40 cents from every one else in the neighborhood.

As Mr. Dunn remarked, capital is an international fluid. It flows into channels of least resistance. The price of capital is affected by the same laws of supply and demand that govern the prices of every other commodity. If it is higher in this country than in some other country for any individual class of enterprises it is because that class of enterprises lacks some feature of fundamental value. In Mr. Dunn's comparison of the operating costs of typical steam and water plants the capital rental for steam is 19 per cent as against 77.4 per cent for water. If by creating public confidence in the stability of investment and otherwise making these projects financially attractive the rate could be reduced say from 7 per cent to 5 per cent the annual cost of a steam unit of power would come down 5.4 per cent and that of the water unit 22 per cent.

One thing capital looks for is earning capacity, and another thing is stability. Nearly all enterprises can get capital at some price because there is an abundance of it; but when any project lacks certainty of ample earning power on the one hand or stability on the other, that fact will be reflected at once in the price of capital which will demand a higher return.

One thing America can do to reduce the rent of the capital which water powers need, is to remove all the unnecessary handicaps with which it is now loaded One of these is the lack of stability. Warned by the losses suffered in the past by many water power investors, cautious people now hesitate to incur similar risks; consequently, the source of capital supply is restricted to that extent and a higher rental prevails. If we can eliminate this disability capital rental will fall and the development of the water powers throughout the entire length and breadth of the land will be stimulated.

One speaker referred to the lower price of money abroad He mentioned the paternalism of Germany in handling their railroads and other enterprises, and by inference at least drew a comparison unfavorable to American bankers and their supposed unreasonable demands. As far as my information goes there is no more ruthless financier than this same German banker. He is certainly no more keen to lend his money to an unprofitable enterprise, or at a lower rate of interest, on account of patriotism, than the American or English or any other banker. During my tour in South America, I learned about some methods of the German bankers doing business in those countries. I found that they exacted rates of interest which even the most rapacious American banker would not think of asking at home. They did it for just one reason, local conditions justified the rate and they charged the market price for their money. They could get it and they are going to continue to get it. You can rest assured that when a foreign banker lends his money to hydroelectric enterprises in his country at lower rates of interest than the American banker does in the United States, it is because the foreign investment is more secure, because experience shows that the foreign government is going to protect that investment and the risk of loss is correspondingly reduced.

This afternoon Mr. Stott spoke about the low cost of power from steam and the increasing severity of the cost competition with which water powers had to contend. The more I study water powers the greater respect I have for steam and if water power is to prevail at all, we must do our utmost to bring its cost down to the lowest possible limit. If steam can get down lower, steam will be used and water power will not be developed. But every time the cost of water power comes down a little bit its use is broadened and a certain number of water powers which otherwise could not be commercially developed are worthy of consideration.

That is the task to which I think we should address ourselves.

The erroneous and misleading impression that has so long prevailed in the minds of many people throughout the land who have not studied the problem carefully and which has been reflected in the views of our Congressmen, that water powers are very cheap and enormously profitable, is being gradually dissipated and the facts are becoming known. Congress needs only to learn the facts to act upon them in an effective and patriotic way with the same singleness of purpose with which we would apply ourselves to an enterprise for a client. But the feeling that water power development is abnormally profitable to the promoter is deep rooted and of long standing. It still prevails in many quarters. Some Congressmen believe that the interests of the public are in some way different from or antagonistic to those of the investor and that it is their duty to safeguard the people's cause by driving a bargain, so to speak, with capital and by trying to see how little they can do to induce investors to put their money into hydroelectric enterprises. It would be unfortunate if the government which is seeking to have its resources developed by private enterprise without contributing its credit or assuming any risks whatever should adopt a policy which will just not accomplish the desired result by reason of over zeal in attempting to drive a bargain with the investor who is in no way whatever obligated to supply funds for such enterprises.

George R. Smith: Since going to Congress I have given this subject consideration from the view point of the public as well as the investor. I take it, from what I have heard tonight, we do not all look at it from the view point of the capitalist, the man who invests his money. Now, I agree with you that there should be certainty of tenure, and there should be certainty of a reasonable return on the investment. I would say, in view of what little I have done in the way of helping along legislation that if the members of this Institute are ashamed of the sort of legislation which is before Congress for its consideration, as is indicated by statements made, that they have another guess coming, that there is nothing quite so bad as some of the remarks would indicate.

Ever since the veto of the James River Bill we have been trying to get legislation through Congress that would protect the public and at the same time protect the investor, and up to the present time we are just as far away from that as we were when we started. I think that the Shields Bill is no better, possibly no worse than previous bills that have been introduced on the subject.

I want to leave this thought with you. Mr. Dunn put his finger on the sore spot when he said that public utilities could be regulated by commissions,—but he failed to say what kind of commissions. Mr. Hugh L. Cooper appeared a little over a year ago before a committee of the House of Representatives, having under consideration the Adamson Water Power Bill, which is similar to the Shields Bill and stated that he was afraid of state legislators and state legislatures because he had seen so many awful things committed by them but had absolute confidence in members of Congress and, therefore, was in favor of Congress enacting a law that would authorize the Secretary of War to regulate the price and service of hydroelectric energy.

A few weeks ago in an article in the *Outlook*, when the Shields Bill was under consideration in the Senate, Mr. Cooper said that public utility commissions created by state legislatures will afford all the protection that is necessary for the public and favored state regulation of hydroelectric companies. I wish Mr: Cooper could understand when he appears before Congress at a time when we are seriously considering a piece of legislation which is so necessary as a thoroughgoing water power bill and makes a statement along one line and then in a short time afterwards makes a statement in the press diametrically opposed to the one he made before Congress, that he cannot be expected to be taken seriously. We understand that Mr. Cooper has shifted his position, but we are not quite so clear as to his motive.

There is a great deal of suspicion abroad concerning the motives of representatives of capital who are advocating water power legislation; some of it is unfounded and some of it has a good foundation, a very good foundation. Now, going back to the matter that I wish to call your attention to, I will say that you have got to permit hydroelectric plants to combine in order to operate them economically. Every man who knows anything about the subject at all, knows that that is one of the fundamental principles of economy in dealing with hydroelectric plants. In some cases a number of these plants have combined, a very considerable number, and the moment plants located in different states are combined, state utility commissions cannot regulate them because the current becomes interstate.

In Minnesota we are about to receive power from Wisconsin where there is a large power plant supplying power to various projects. At the present time, Minneapolis, gets its current from Taylor Falls on the state boundary line between Minnesota and Wisconsin. How can a Minnesota Commission regulate current generated in Wisconsin and brought into our state? How can it tell what is a fair rate under that situation? How can it inspect the books of a plant located in Wisconsin, which sells power to the Consumers' Power Company located in Minnesota? The Minnesota Commission has jurisdiction as to how much the Consumers' Power Company, which is nothing more or less than a distributing company, pays for its current but it has no way of determining whether the price paid by the Consumer's Power Company to the Wisconsin company is a fair and reasonable charge, and, therefore, is unable to determine what would be a fair and just rate to patrons of the Consumers' Power Company.

Nothing short of a Federal Commission authorized to work in conjunction with state commissions will meet the situation which I have called attention to. Besides, under a Federal Commission, the work now being done by the Secretary of War, the Secretary of Interior and the Secretary of Agriculture, could be brought under a single head thus effecting a great saving to the government and assuring efficient regulation which would rebound to the benefit of the investor and the consumer.

The moment that the promoters, the investers, the engineers and the associations that are giving their time to this subject come to Congress with a fair proposition, fair to the public and fair to the investor, Congress will join hands with them in working out an efficient law. Congress is looking for light, it is looking for information. Members of Congress are also anxious to know why they are persecuted for daring to offer any objection to impending legislation that is offered by what is known as the water power monopoly.

Why, we know and you know better than I do, that the water power interests of this country are controlled by a very few men, the whole policy is dictated by a very few men. Mr. J. P. Morgan of New York City is one of the leadingfactors, and the General Electric Companies is the great big institution, with its subsidiaries, that controls the situation. I do not object to the monopoly because the development of hydroelectric power economically is a natural monopoly. The thing I object to is the refusal on the part of those owning the monopoly to admit that there is a monopoly and I object to their attempt to deceive the public as to the existence of such a monopoly, in order to defeat legislation having for its purpose the control and regulation of such a monopoly.

Mr. Cooper says in his article in *The Outlook*, that it is not a monopoly—he laughs at the idea, he scoffs at it— and yet we know it is a monopoly. Why do the water power interests try to deceive the public? What can be their purpose? Under such a condition of affairs is it surprising that members of Congress as well as the public, look with suspicion upon any suggestion coming from owners of this monopoly. But as long as the water power interest suppress the facts concerning the monopolistic tendencies of hydroelectric development, Congress of the United States cannot be blamed for its refusal to be rushed off its feet in the consideration of water power legislation.

D. B. Rushmore: I need not say that I came here absolutely as an individual. I came here in my capacity as a member of the Institute, and as a man who has spent his life on water power developments, and I will be frank with some of my experiences. I have never lost money to any extent in anything else except water power development. I have had a gentleman in New York tell me that he has had in one autumn sixty-six men who controlled water powers locally and also men from different countries come to him and ask him to help them to raise money for those water power enterprises. Now, there is one waterpower, not very far from New York, in which the man who controlled it for years was a friend of a friend of mine. This friend happened to call at our office, and he was turned over to me. He had the right to a waterpower and wanted to raise money to finance it, but could not do it. He had been working on it for years and no one would take it up. I had a friend of mine look it up and he said it was no good, that it would not pay, that it did not have a market. The proposition was finally taken to Chicago to people who were somewhat familiar with it. I know they had a difficult time raising the money, people did not want to go into it, they said it did not look good to them. The only place they could go to raise the money was to bankers familiar with the project. In my experience as an engineer I have always seen the pressure come from the other side. I presume there are in New York every year hundreds of men who control complete situations trying to raise the money for them. If you talk to a man who does not know anything about a waterpower, he will not listen to you. It seems to me there has been a great misconception about this matter.

Mr. Dunn has dealt with bankers and knows the difficulties of raising money and in my opinion his paper will add very much to the beneficial result of our meeting here. Mr. Townley's discussion can also be brought to the attention of those who are in any way interested in this very broad and important subject. The financing of water powers, as Mr. Townley said, very truly, is dependent on us. Would any of us invest our money in them. I know a couple of bond brokers who sell bonds in the Mohawk Valley. They go into Amsterdam and offer to sell farmers public utility and water power bonds, and what the farmers pay for the bonds depends on the conditions on which the water power can be installed and operated. The banker goes around and gathers up various opinions and finds out what the people will take the bonds for.

The time is here for a new era of publicity. We are all afraid of the things we do not know—what is behind the doors and what is not brought out is always largely open to suspicion. Take the public into your confidence, work with the public, put the cards right down on the table before the public and show them just what you have.

Oscar T. Crosby: The political problems confronting us in the development of our water powers are these:

First, to what extent shall the authority of the general government, as distinguished from that of the several states, determine the location, physical construction and physical operation of water power plants?

Second, what authority shall control the financial operations of water power companies, including in this phase the control of rates?

Third, assuming these two questions as settled in one way or another, what principle should underlie the control of rates, of financial organization, of return to capital and of possible acquisition by public authority of private property involved in water power developments? Let us take up these questions in the order I have indicated.

Navigable streams are now fully recognized as being under the jurisdiction of the general government. There is no contention as to the right of that government to determine for or against the placing in such streams of any obstructions whatever. There is very grave contention as to the conditions which may be constitutionally attached, or which in wise policy should be attacked, to a permission given by the general government in any particular case. Should the sole interest of navigation be consulted, with no consideration affecting investment except that the proposed works should not result in navigation costs greater than those which otherwise would fall upon the public?

Should consideration of flood effects, as distinguished from navigation effects, also enter? Should questions of injury and advantage to agricultural lands, through drainage or irrigation be considered by the United States authorities?

In raising these questions, we raise a series of constitutional issues which it would be long and hard to settle. Happily, they need not be settled. If Smith and Jones have overlapping and tangled rights in respect to a tract of land, and if Brown wishes to use the land, then, without waiting for the law's delay, the proposed use of the land may be effected by a joint grant, or by parallel grants from Smith and Jones to Brown. Let Smith be Uncle Sam, let Jones be the State of Ohio, and let Brown be a water power company, and we may proceed to determine the physical questions surrounding any situation in a navigable stream. We may even go further, and thus cover the difficulties as presented by the question as to what *is* a navigable stream, according to the Constitution. The existing legal definitions are such as would let almost any creek into the dignified company of streams, which must recognize in Uncle Sam their overlord.

In my early years, as a young officer of engineers, I examined a "navigable stream (?)" in a buggy. Rubber boots would have done as well, but for the length of the thing.

However extreme the case, we may rest assured that a handsome appropriation will settle most "state's rights" doubts as to the navigability question. But if no appropriation be involved a real issue, affecting validity of permits, remains to be solved. Co-operation of Smith and Jones is the true, practical solution of this, and of the other doubtful points concerning floods, drainage, etc.

But the United States appears in quite a different role than that of overlord and largess-giver, when we regard the public domain in our Western States. Are we dealing here with a sovereign, or with a mere landlord-proprietor, subject to the laws of the local sovereign—the state? In my judgment, that is the true view of the case. But it is a much contested point.

As a citizen of the United States, concerned that all states, east and west, should be in the same relation to lands within their bounds, I should be loath to see any assumption of an *imperium in imperio*, by the general government, because it holds as trustee certain lands in certain Western States. As one easterner, I want to register my cession of title in these lands to the people of the states within which they live. But if this battle cannot be won, then it may at least be compromised by the same principle of co-operation in grants that has just been proposed in the case of navigable streams. But this compromise should go no further than is required for determining the physical elements,—the construction elements—of each case.

When we meet the matter of financial control in all its aspects, I am firmly convinced that the states alone should determine. Even if the courts should decide that the general government has a right to enter this field, yet would I contend that as a matter of policy it should not enter it.

There are good men in the Washington bureaucracy, but there are few efficient bureaucracies in all the world. Can men be established in this city to administer wisely through subordinates the distant affairs of a Californian hydroelectric company? Will it be a bearable burden if an operator in Oregon must communicate with Washington in all those intimate ways which have been made familiar to us by the Public Utility Commissions of our states? Is the burden not now heavy enough when recourse must be had in so many matters to boards sitting in state capitols? And shall we have in the same state one control for steam plant generation, and another for water generation of electricity? What confusion! What discouragement!

Let us hope that this madness of centralization of control in Washington will pass.

Let us now consider the *principles* of control, without respect to the question as to which of our dual sovereignties is to exercise that control.

Men invest money in public utilities, not in order to charge particular rates for service, but in an effort to earn a return on the capital invested. That is the objective. A just and reasonable rate is a rate that will cause money and energy to flow into the enterprise which performs a given service, whether that service be the sale of electric energy or the sale of bread or shoes.

Then since it is right that there should be control of monopolies and since public utilities are necessarily monopolies (in the long run and in respect to at least some part of their clientele), let this control express itself in contracts relating in plain terms and in specific figures the return on capital. Rates may then be left to those who conduct the operations, subject, of course, to the usual common law rule against discriminatory practises.

These contracts as to return on capital may vary very widely from case to case; they should generally be on a sliding scale basis, providing lower returns in proportion to assured success, but they should be specific and clear. Let us get away from the unreasonable "rule of reasonableness"—misrule of unreasonableness—which now leaves rates and returns almost wholly to the guess of commissioners. Most of them are good men, but good men are not always wise men, and even wise men should not be left to decide vast property interests without guiding principles which put all parties on notice as to their rights. Let us recognize that the inventor has destroyed the old common law rule of reasonableness, which was the rule of custom. Now the ferment of invention has, for nearly a hundred years, prevented custom from taking a "permanent set," and this ferment is destined to continue. Customary rates will not be established. Contract rates may be fixed to a limited extent, chiefly as maxima. But there is no difficulty in *fixing returns* to *capital* on a sliding scale in each contract for a public service.

And as to the final chapter, the possible taking over of a property by the public, we hear far too much about it. The old law of eminent domain seems to be forgotten. No "perpetual franchise" can hold against the right of the government to take anything it wants. No fixed term franchise can hold against that right. A grant of today may be taken tomorrow. But private property must be paid for if thus taken. Now, the terms of payment may be fixed far in advance, or may be left to a jury at any time. If we had contracts fixing possible (not guaranteed) returns on capital, those contracts interpreted in the light of actual results obtained by operation, and with known investment figures, would render relatively simple the now fearsome task of fixing a condemnation value.

I append a copy of the bill proposed by me some years ago to cover the matter of permits for water-power construction.

(See proposed bill referred to by Mr. Crosby in hearing before National Waterways Commission, Washington, November, 1911, pages 136 and 137.)

Gano Dunn: I want to do service to a friend and to say to the Honorable Congressman that he understood Mr. Baekeland exactly the reverse of what Mr. Baekeland meant about Congress. Mr. Baekeland's experience has been the same as that of all the rest of us when we came down here—we have been received very courteously and listened to with such attention that we have been made to feel that every member of Congress or the committee we have gone before has been extremely desirous of drawing out all the facts. This has caused us to revise some of our former false opinions to the contrary.

I would like to read to the Congressmen and others who may be interested, the official policy of the American Institute of Electrical Engineers in regard to these matters, especially in view of his suggestion that we develop and bring out a bill for specific suggestions as to how water-powers should be handled: "The governing body of the Institute has continued its special committee (on water power) in consequence of these successive invitations in view of the apparent appreciation on the part of the government that the services rendered by the American Institute of Electrical Engineers were scientific and professional and not commercial or political, that its committees dealt with fundamental engineering and economic principles of hydro-electric development that were outside the field of controversy, and that the function of the Institute being scientific and professional and not commercial or political, its status was one involving a high degree of disinterestedness in respect to matters on which its technical advice was sought."

Mr. Baekeland referred to an address which I had the honor of making before the Washington Society of Engineers some time ago, in which he mistakenly reported me as saying that engineers ought never to mix in politics and other things. What I said was that in the appointment of the Naval Advisory Board, I believed for the first time in history the engineer, as such, had been invited to sit on the bench of Government with the statesman and co-operate with and help him; but I also said that the engineer should never go so far as to think that he can take the place of the statesman. The function is different and requires a different kind of man. The engineer is not big enough to do both things, and if we appointed an engineer as Secretary of State, our diplomacy would be likely to suffer. Therefore, I feel that we should stay in our own province as technical experts, and advise about the things we know, we should go before the various committees of Congress and answer inquiries about these things, but it is to them we should leave the other questions of what bills should be drawn and what kind of political bodies should be created to do the regulating and administering of the affairs of the government generally. Something toward this aim is what we hoped to accomplish in organizing this meeting here for the discussion of water-powers.

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THE RELATION OF PURE SCIENCE TO INDUSTRIAL RESEARCH

PRESIDENT'S ADDRESS

BY J. J. CARTY

IT IS not strange that many years ago Huxley, with his remarkable precision of thought and his admirable command of language, should have indicated his dissatisfaction with the terms "pure science" and "applied science", pointing out at the same time that what people call "applied science" is nothing but the application of pure science to particular classes of problems. The terms are still employed, possibly because, after all, they may be the best ones to use, or perhaps our ideas, to which these expressions are supposed to conform, have not yet become sufficiently definite to have called forth the right words.

It is not the purpose of this address, however, to suggest better words or expressions, but rather to direct attention to certain important relations between purely scientific research and industrial scientific research which are not yet sufficiently understood.

Because of the stupendous upheaval of the European war with its startling agencies of destruction—the product of both science and the industries—and because of the deplorable unpreparedness of our own country to defend itself against attack, there has begun a great awakening of our people. By bringing to their minds the brilliant achievements of the membership of this Institute in electric lighting and power and communications and by calling their attention to the manifold achievements of the members of our sister societies in mechanical and mining and civil engineering, and the accomplishments of our fellow-workers, the industrial chemists, they are being aroused to the vital importance of the products of science in the national defense.

Arising out of this agitation comes a growing appreciation of the importance of industrial scientific research, not only as an aid to military defense but as an essential part of every industry in time of peace.

Industrial research, conducted in accordance with the principles of science, is no new thing in America. The department which is under my charge, founded nearly forty years ago to develop, with the aid of scientific men, the telephone art, has grown from small beginnings with but a few workers to a great institution employing hundreds of scientists and engineers, and it is generally acknowledged that it is largely owing to the industrial research thus conducted that the telephone achievements and development in America have so greatly exceeded those of other countries.

With the development of electric lighting and electric power and electric traction which came after the invention of the telephone, industrial scientific research laboratories were founded by some of the larger electrical manufacturing concerns and these have attained a world-wide reputation. While vast sums are spent annually upon industrial research in these laboratories, I can say with authority that they return to the industries each year improvements in the art which, taken all together, have a value many times greater than the total cost of their production. Money expended in properly directed industrial research, conducted on scientific principles, is sure to bring to the industries a most generous return.

While many concerns in America now have well organized industrial research laboratories, particularly those engaged in metallurgy and dependent upon chemical processes, the manufacturers of our country as a whole have not yet learned of the benefits of industrial scientific research and how to avail themselves of it.

I consider that it is the high duty of our Institute and of every member composing it, and that a similar duty rests upon all other engineering and scientific bodies in America, to impress upon the manufacturers of the United States the wonderful possibilities of economies in their processes and improvements in their products which are opened up by the discoveries in science. The way to realize these possibilities is through the medium of industrial research conducted in accordance with scientific principles. Once it is made clear to our manufacturers that industrial research pays, they will be sure to call to their aid men of scientific training to investigate their technical problems and to improve their processes. Those who are the first to avail themselves of the benefits of industrial research will obtain such a lead over their competitors that we may look forward to the time when the advantages of industrial research will be recognized by all.

Industrial scientific research departments can reach their highest development in those concerns doing the largest amount of business. While instances are not wanting where the large growth of the institution is the direct result of the care which it bestowed upon industrial research at a time when it was but a small concern, nevertheless conditions to-day are such that without cooperation among themselves the small concerns cannot have the full benefits of industrial research, for no one among them is sufficiently strong to maintain the necessary staff and laboratories. Once the vital importance of this subject is appreciated by the small manufacturers many solutions of the problem will promptly appear. One of these is for the manufacturer to take his problem to one of the industrial research laboratories already established for the purpose of serving those who cannot afford a laboratory of their own. Other manufacturers doing the same, the financial encouragement received would enable the laboratories to extend and improve their facilities so that each of the small manufacturers who patronizes them would in course of time have the benefit of an institution similar to those maintained by our largest industrial concerns.

Thus, in accordance with the law of supply and demand, the small manufacturer may obtain the benefits of industrial research in the highest degree and the burden upon each manufacturer would be only in accordance with the use he made of it, and the entire cost of the laboratories would thus be borne by the industries as a whole, where the charge properly belongs. Many other projects are now being considered for the establishment of industrial research laboratories for those concerns which cannot afford laboratories of their own, and in some of these cases the possible relation of these laboratories to our technical and engineering schools is being earnestly studied.

Until the manufacturers themselves are aroused to the necessity of action in the matter of industrial research there is no plan which can be devised that will result in the general establishment of research laboratories for the industries. But once their need is felt and their value appreciated and the demand for research facilities is put forth by the manufacturers themselves, research laboratories will spring up in all our great centers of industrial activity. Their number and character and size, and their method of operation and their relation to the technical and engineering schools, and the method of their working with the different industries, are all matters which involve many interesting problems—problems which I am sure will be solved as they present themselves and when their nature has been clearly apprehended.

In the present state of the world's development there is nothing which can do more to advance American industries than the adoption by our manufacturers generally of industrial research conducted on scientific principles. I am sure that if they can be made to appreciate the force of this statement, our manufacturers will rise to the occasion with all that energy and enterprise so characteristic of America.

So much has already been said and so much remains to be said urging upon us the importance of scientific research conducted for the sake of utility and for increasing the convenience and comfort of mankind, that there is danger of losing sight of another form of research which has for its primary object none of these things. I refer to pure scientific research.

In the minds of many there is confusion between industrial scientific research and this purely scientific research, particularly as the industrial research involves the use of advanced scientific methods and calls for the highest degree of scientific attainment. The confusion is worse because the same scientific principles and methods of investigation are frequently employed in each case and even the subject matter under investigation may sometimes be identical.

The misunderstanding arises from considering only the subject matter of the two classes of research. The distinction is to be found not in the subject matter of the research, but in the motive.

The electrical engineer, let us say, finding a new and unexplained difficulty in the working of electric lamps, subjects the phenomenon observed to a process of inquiry employing scientific methods, with a view to removing from the lamps an objectionable characteristic. The pure scientist at the same time investigates in precisely the same manner the same phenomenon, but with the purpose of obtaining an explanation of a physical occurence, the nature of which cannot be explained by known facts. Although these two researches are conducted in exactly the same manner, the one nevertheless comes under the head of industrial research and the other belongs to the domain of pure science. In the last analysis the distinction between pure scientific research and industrial scientific research is one of motive. Industrial research is always conducted with the purpose of accomplishing some utilitarian end. Pure scientific research is conducted with a philosophic purpose, for the discovery of truth, and for the advancement of the boundaries of human knowledge.

The investigator in pure science may be likened to the explorer who discovers new continents or islands or hitherto unknown territory. He is continually seeking to extend the boundaries of knowledge.

The investigator in industrial research may be compared to the pioneers who survey the newly discovered territory in the endeavor to locate its mineral resources, determine the extent of its forests, and the location of its arable land, and who in other ways precede the settlers and prepare for their occupation of the new country.

The work of the pure scientists is conducted without any utilitarian motive, for, as Huxley says, "that which stirs their pulses is the love of knowledge and the joy of discovery of the causes of things sung by the old poet—the supreme delight of extending the realm of law and order ever farther towards the unattainable goals of the infinitely great and the infinitely small, between which our little race of life is run." While a single discovery in pure science when considered with reference to any particular branch of industry, may not appear to be of appreciable benefit, yet when interpreted by the industrial scientist, with whom I class the engineer and the industrial chemist, and when adapted to practical uses by them, the contributions of pure science as a whole become of incalculable value to all the industries.

I do not say this because a new incentive is necessary for the pure scientist, for in him there must be some of the divine spark and for him there is no higher motive than the search for the truth itself. But surely this motive must be intensified by the knowledge that when the search is rewarded there is sure to be found, sooner or later, in the truth which has been discovered, the seeds of future great inventions which will increase the comfort and convenience and alleviate the sufferings of mankind.

By all who study the subject, it will be found that while the discoveries of the pure scientist are of the greatest importance to the higher interests of mankind, their practical benefits, though certain, are usually indirect, intangible or remote.

Pure scientific research unlike industrial scientific research can not support itself by direct pecuniary returns from its discoveries.

The practical benefits which may be immediately and directly traced to industrial research, when it is properly conducted, are so great that when their importance is more generally recognized industrial research will not lack the most generous encouragement and support. Indeed, unless industrial research abundantly supports itself, it will have failed of its purpose.

But who is to support the researches of the pure scientist, and who is to furnish him with encouragement and assistance to pursue his self-sacrificing and arduous quest for that truth which is certain as time goes on to bring in its train so many blessings to mankind? Who is to furnish the laboratories, the funds for apparatus and for traveling and for foreign study?

Because of the extraordinary practical results which have been attained by scientifically trained men working in the industrial laboratories and because of the limited and narrow conditions under which many scientific investigators have sometimes been compelled to work in universities, it has been suggested that perhaps the theater of scientific research might be shifted trom the university to the great industrial laboratories which have already grown up or to the even greater ones which the future is bound to bring forth. But we can dismiss this suggestion as being unworthy.

Organizations and institutions of many kinds are engaged in pure scientific research and they should receive every encouragement, but the natural home of pure science and of pure scientific research is to be found in the university, from which it cannot pass. It is a high function of the universities to make advances in science, to test new scientific discoveries and to place their stamp of truth upon those which are found to be pure. In this way only can they determine what shall be taught as scientific truth to those who, relying upon their authority, come to them for knowledge and believe what they teach.

Instead of abdicating in their favor, may not our universities, stimulated by the wonderful achievements of these industrial laboratories, find a way to advance the conduct of their own pure scientific research, the grand responsibility for which rests upon them. This responsibility should now be felt more heavily than ever by our American universities, not only because the tragedy of the great war has caused the destruction of European institutions of learning, but because even a worse thing has happened. So great have been the fatalities of the war that the universities of the old world hardly dare to count their dead.

But what can the American universities do, for they, like the pure scientists, are not engaged in a lucrative occupation. Universities are not money-making institutions, and what can be done without money?

There is much that can be done without money. The most important and most fundamental factor in scientific research is the mind of a man suitably endowed by nature. Unless the scientific investigator has the proper genius for his work, no amount of financial assistance, no apparatus or laboratories, however complete, and no foreign travel and study however extensive, will enable such a mind to discover new truths or to inspire others to do so. Judgment and appreciation and insight into character on the part of the responsible university authorities must be applied to the problem, so that when the man with the required mental attributes does appear he may be appreciated as early in his career as possible. This is a very difficult thing to do indeed. Any one can recognize such a man after his great achievements have become known to all the world, but I sometimes think that one who can select early a man who has within him the making of the scientific discoverer must have been himself fired with a little of the divine spark. Such surely was the case with Sir Humphrey Davy, himself a great discoverer, who, realizing the fundamental importance of the man in scientific discovery, once said that Michael Faraday, whose genius he was prompt recognize, constituted his greatest discovery.

I can furnish no formula for the identification of budding genius and I have no ready-made plan to lay before the universities for the advancement of pure scientific research. But as a representative of engineering and industrial research, having testified to the great value of pure scientific research, I venture to suggest that the university authorities themselves might well consider the immense debt which engineering and the industries and transportation and communications and commerce owe to pure science, and to express the hope that the importance of pure scientific research will be more fully appreciated both within the university and without, for then will come—and then only—that sympathetic appreciation and generous financial support so much needed for the advancement of pure scientific research in America.

While there are many things—and most important things—which the universities can do to aid pure science without the employment of large sums of money, there are nevertheless a great many things required in the conduct of pure scientific research which can be done only with the aid of money. The first of these I think is this:

When a master scientist does appear and has made himself known by his discoveries, then he should be provided with all of the resources and facilities and assistants that he can effectively employ, so that the range of his genius will in no way be restricted for the want of anything which money can provide.

Every reasonable and even generous provision should be made for all workers in pure science, even though their reputations have not yet become great by their discoveries, for it should be remembered that the road to great discoveries is long and discouraging and that for one great achievement in science we must expect numberless failures.

I would not restrict these workers in pure science to our great universities, for I believe that they should be located also at our technical schools, even at those with the most practical aims. In such schools the influence of a discoverer in science would serve as a balance to the practical curriculum and familiarize the student with the high ideals of the pure scientist and with his rigorous methods of investigation. Furthermore, the time has come when our technical schools must supply in largely increasing numbers men thoroughly grounded in the scientific method of investigation for the work of industrial research.

Even the engineering student, who has no thoughts of industrial research, will profit by his association with the work of the pure scientist, for if he expects ever to tread the higher walks of the engineering profession he must be qualified to investigate new problems in engineering and devise methods for their solution and for such work a knowledge of the logical processes of the pure scientist and his rigorous methods of analyzing and weighing evidence in his scrupulous search for the truth will be of the greatest value.

Furthermore, the engineering student should be taught to appreciate the ultimate great practical importance of the results of pure scientific investigation and to realize that pure science furnishes to engineering the raw material, so to speak, which he must work into useful forms. He should be taught that after graduation it will be most helpful to him and even necesary, if he is to be a leader, to watch with care the work of the pure scientist and to scrutinize the reports of new scientific discoveries to see what they may contain that can be applied to useful purposes and more particularly to problems of his own which require solution. There are many unsolved problems in applied science, to-day which are insoluble in the present state of our knowledge, but I am sure that in the future, as has so often happened in the past, these problems will find a ready solution in the light of pure scientific discoveries yet to be made. When thus regarded the work of the pure scientist should be followed with most intense interest by all of those engaged in the application of science to industrial purposes. Acquaintance, therefore with the pure scientist, with his methods and results, is of great importance to the student of applied science. I believe that there is need of a better understanding of the relations between the pure scientist and the applied scientist and that this understanding would be greatly helped by a closer association between the pure scientist and the students in the technical schools.

While I have drawn a valid distinction between the work of the two, they nevertheless have much in common. Both are concerned with the truth of things, one to discover new truths and the other to apply these truths to the uses of man. While the object of the engineer is to produce from scientific discoveries useful results, these results are for the benefit of others. They are dedicated to the use of mankind and, as is the case with the pure scientist, they should not be confused with the pecuniary compensation which the engineer himself may receive for his work for this compensation is slight, often infinitesimally so, compared with the great benefits received by others. Like the worker in pure science, the engineer finds inspiration in the desire for achievement and his real reward is found in the knowledge of the benefits which others receive from his work.

There are many other things which might be discussed concerning the conduct of pure scientific research in our universities and technical schools, but enough has been said to make it plain that I believe such work should be greatly extended in all of our American universities and technical institutions. But where are the universities to obtain the money necessary for the carrying out of a grand scheme of scientific research? It should come from those generous and public spirited men and women who desire to dispose of their wealth in a manner well calculated to advance the welfare of mankind, and it should come from the industries themselves, which owe such a heavy debt to science.

While it cannot be shown that the contribution of any one manufacturer or corporation to a particular purely scientific research will bring any return to the contributor or to others, it is certain that contributions by the manufacturers in general and by the industrial corporations to pure scientific research as a whole will in the long run bring manifold returns through the medium of industrial research conducted in the rich and virgin territory discovered by the scientific explorer.

It was Michael Faraday, one of the greatest of the workers in pure science, who in the last century discovered the principle of the dynamo electric machine. Without a knowledge of this principle discovered by Faraday the whole art of electrical engineering as we know it to-day could not exist and civilization would have been deprived of those inestimable benefits which have resulted from the work of the members of this Institute.

Not only Faraday in England, but Joseph Henry in our own country and scores of other workers in pure science have laid the foundations upon which the electrical engineer has reared such a magnificent structure.

What is true of the electrical art is also true of all of the other arts and applied sciences. They are all based upon fundamental discoveries made by workers in pure science, who were seeking only to discover the laws of nature and extend the realm of human knowledge.

By every means in our power, therefore, let us show our appreciation of pure science and let us forward the work of the pure scientists, for they are the advance guard of civilization. They point the way which we must follow. Let us arouse the people of our country to the wonderful possibilities of scientific discovery and to the responsibility to support it which rests upon them, and I am sure that they will respond generously and effectively. Then I am confident that in the future the members of this Instutite, together with their colleagues in all of the other branches of engineering and applied science, as well as the physician and surgeon, by utilizing the discoveries of pure science yet to be made, will develop without number marvelous new agencies for the comfort and convenience of man and for the alleviation of human suffering. These, gentlemen, are some of the considerations which have led me here in my presidential address to urge upon you the importance of a proper understanding of the relations between pure science and industrial research.

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STANDARDIZATION

BY C. LE MAISTRE

ALLOW me to commence these remarks by saying how deeply sensible I am of the honor of addressing this representative gathering of American electrical engineers. Thoughtful Europeans, as Lord Bryce well said, have begun to realize the increasing influence of this vast country in the affairs of the world, and the splendor of the part reserved to you in the development of civilization. A brief visit to your hospitable shores has been an inspiration and has enabled me to appreciate, in some small measure, the freedom of your thought, and the breadth of your conceptions. Such is the grandeur of your outlook that I can but echo what was so beautifully expressed by one of the orators at the recent Harvard commencement exercises, namely, that the world needs you and the world will heed you if you but acquit yourselves as men!

So much has been written regarding standardization, and the art has become so necessary to progress, and is so familiar to many of you, that I cannot hope to do more than focus your ideas on a few of the more important aspects of the subject. I shall also try to bring into prominence some of the points connected with the development of engineering standards in Great Britain, which I hope may be of interest, more especially as in order to minimize overlapping and obviate piecemeal methods, the question of co-ordinating the various individual methods in one homogeneous body is occupying the serious attention of competent authorities in this country.

In matters electrical, national and international standardization are so intimately connected that it is scarcely possible to speak of the one without discussing the other. Indeed, international standardization, a barbarous term it is true, but a difficult one to supplant, would seem to be the natural development from the experience gained in the practical application of national standards.

It was stated on one occasion, I remember, that the earliest record of standardization was to be found in the introduction of the Greek alphabet initiated by Xerxes and which was refused by China and Russia. However that maybe, the most notable step in the realization of engineering standards, in so far as Great Britain is concerned, was in 1841, when Sir Joseph Whitworth introduced his standard screw thread. When urging the necessity for standardization, he illustrated his argument by mentioning that candles and candle-sticks were in use in almost every house, and nothing could be more convenient than for the candles to fit accurately into the sockets of the candle sticks, which they seldom did. The lesson taught by his illustration lies at the root of standardization and necessarily carries with it disadvantage to the few for the advantage to the many.

Then we come to the Standards Committee of this Institute, of which Prof. Crocker was the first Chairman, which reported on electrical standardization in 1898. The splendid pioneer work accomplished by that committee has been an incentive to many others and whatever form the proposed central organization may take, the Standards Committee of this Institute will doubtless retain intact its distinctive character whilst supplementing and extending its activities.

Several factors, including keen competition from outside, the legitimate demands of labor for a higher standard of living, coupled with the desire of capital for a better return, have compelled the electrical, in common with the whole engineering industry, to introduce modern order and system into all its methods of production. Former individualistic methods have been forced to give way to co-ordination and collective effort. It is, in fact, co-operation which gives the highest value to individual effort. This, if voluntary and not compulsory, will help to maintain quality.

Now, these improvements which have already resulted in marked benefits, must not only be maintained, but continually added to if the full advantages are to be reaped. Inevitably the necessity of standards to which the products of the workshops may be referred, has manifested itself just as much as fixed standards of weights and measures.

Of course, the individual gain, economically, in private workshop standardization is acknowledged great to the producer for it tends towards interchangeability of working parts, lessens maintenance charges and stores; crystallization, however, which would tend to impede and in some cases stultify progress must be jealously guarded against if monopolies are to be avoided and the purchaser is not to be deprived of the benefit of competitive effort and inventive genius. If, therefore, through some comprehensive centralized body, the users and producers alike can be persuaded to accept an agreed standard, the community interests of buyer and seller are thereby realized and a high average efficiency secured. Generally speaking, satisfactory standardization, whether national or international, has usually been arrived at not by one section of the community imposing its opinions on the other, but rather as the result of co-operative action on the part of all concerned.

Experience has clearly shown that such procedure does not lower the standard, but if anything tends rather to raise it. It reflects, in effect, the consensus of opinion as to what constitutes best modern practise. Such standardization is only arrived at by common consent of the governed who take full part in the discussions and in the initiating and working out of the actual details of the specifications to be recommended for public use. This is one of the chief reasons why the work of the Engineering Standards Committee of Great Britain is so widely adopted—because of the utmost care which is taken, at the very outset, to insure that all who have or could possibly have any interest in the proposed standardization shall have an adequate representation on the Committee drafting the recommendation. This representation is usually effected through the recognized societies and associations of the particular engineers or trades concerned. Such methods register the views of the experts in manufacture as well as those intimately acquainted with the conditions under which machinery and apparatus are employed in every day service.

Undoubtedly, mutual concession and ultimate agreement between the parties interested tend towards uniformity of practise, avoidance of waste, elimination of harsh and unnecessary conditions, and last, but by no means least, bring about a feeling of mutual confidence, such as could not be realized by isolated action on the part of either, however honorable and straightforward it may be.

Again, though much time and labor be occupied in preparing such standard specifications, additions and emendations demanded by experience and new developments must be provided for, and consequently, the specifications must be reviewed annually and thus eliminate undesirable stereotyping of procedure. Such revisions must also be promptly and efficiently dealt with. The standards should have no other authority than that of commom consent. In fact, it is public opinion which gives them their dynamic force, and all progress would be arrested if there was a possibility of their being enacted into statutory law.

The initiation in 1901 of the British Engineering Standards Committee, the greatest private voluntary effort of the kind, is due to Sir John Wolfe Barry, K. C. B., whose name is a household word amongst British engineers. His commanding influence in the engineering world, and the deep respect in which he is held by the whole profession has probably been the greatest factor in bringing this organization to its present unassailable position. It had a small beginning, but has increased in scope and efficiency till today its influence is felt and its specifications acknowledged and worked to throughout practically the whole of the Empire. Its main committee, or Senate, is composed of the official representatives of the five leading engineering institutions; to this committee falls the whole administration of the work, the raising of the necessary funds, the controlling of the expenditure and the ratification of all reports and specifications presented by the various sectional committees prior to publication. The sectional committees are instituted by this main committee which appoints the respective chairmen. Under this main committee there are some 80 sectional sub-committees and small panels, the membership being between 500 and 600. The sectional committees consist of representatives of the various government departments, consulting engineers, manufacturers and users, as well as representatives of the technical societies and trade associations interested in or affected by the subjects under consideration. The sectional committees, and in some cases the sub-committees, decide the broad lines upon which the specifications are to be drawn up and then delegate the working out of the preliminary details to a sub-committee or panel. If necessary, evidence is taken, the advice of experts is sought, and in this way all parties are consulted and have a proper voice in the initial proposals, thus avoiding much subsequent friction which might otherwise occur.

The specifications of the committee find an increasingly wide adoption, being more and more substituted for the various government and municipal specifications hitherto employed. They deal with the main technical clauses, leaving questions of contact to be dealt with by the purchaser.

The electrical section of the committee, which forms an important part of the whole, is under the able chairmanship of Sir John Snell. It has recently been entirely reorganized, and is now *ipso facto* the British National Committee of the International Electrotechnical Commission, or the I. E. C. as it is called. Thus the national and international interests of the British electrical industry are under one organization with increase of efficiency in every way. Dr. R. T. Glazebrook, C. B., is the chairman of the committee when I. E. C. matters are under discussion.

In drawing up industrial standards covering electrical machinery and apparatus, experimental investigations frequently become necessary in order to establish the facts underlying the principles involved, and it is in this connection that the National Physical Laboratory has been and is so conspicuously useful to the Standards Committee. It is in effect our official testing bureau, and our ultimate authority, and it acts in an advisory capacity in practically all the work. The success of the British Standards Committee is due in large measure to the energy, foresight and ability of Mr. Leslie Robertson, the Chief Secretary, whose geniality and intimate knowledge of men and affairs have enabled him to cope successfully with problems many another would have hesitated to undertake. Going on a government mission he perished with Lord Kitchener on June 6th last, an irreparable loss to us all.

The commerce of the world, due to the wondrous development of communication, has, one might almost say, in spite of the artificial barriers set up by the different nations, become more and more international. It is, of course, inevitable that the standardization rules for electrical machinery in use in the various countries should differ in detail because conditions of manufacture necessarily differ and so influence the rules. Yet the method of ascertaining the actual rating of a machine, paper rating one might almost call it, so important to the prospective purchaser, especially when separated from the maker by long distances, as is often the case, should surely be identical in all countries, since it depends on the physical and mechanical properties of the machine, and is not a question of geographical position. This is peculiarly the work of the I. E. C.

Theory and practise are perhaps more closely allied in electrical engineering than in any other applied science, and it is therefore, important in the application to industrial purposes of the laws of electrotechnics, that the rules which form the basis of technical specifications and consequently of commercial contracts, should be as free as possible from ambiguity and complications, yet at the same time sufficiently definite and comprehensive to insure a satisfactory means of comparison between the machine supplied and the standard.

The problem is, however, more intricate than that of dealing with simple pieces of mechanism, for it involves the consideration of the peculiar properties of the materials forming the essential portions of the machine. For instance, the conductivity of the copper or the permeability of the iron can be measured with substantial accuracy and, what is more important still, without the portion tested being destroyed or damaged. The mechanical strength of the materials also can be estimated with sufficient accuracy from the result of definite and easily carried out tests on samples of the materials, with almost complete assurance that the bulk material will have the same properties and therefore behave in the same way as the samples tested. These particular properties are, in fact, of such a nature that they can be specified with precision, and moreover, are not appreciably affected by the elements of time. When the question of the insulating materials, however, is considered, the problem is of course, very different, and one can but acknowledge that owing to their inherent properties, the insulating materials employed at present, come into an entirely different category. They are governed by no well-defined laws, as in the case of the copper and iron, their properties are variable and alter largely for very small changes in the conditions of manufacture, as well as those under which they are employed in the completed machine. The resistance they offer to the passage of the current constantly changes, and tests on samples are, therefore, not very satisfactory, as varying the length of the test may give results differing considerably in magnitude. One of the most important problems, therefore, is the settling of the limits which it is considered necessary to impose in order to insure that the principal causes of destruction of the insulating materials, the heating combined with the time element, shall be kept well within safe limits.

A clear distinction exists between an "international standard of quality" and an "international rating." The international acceptance of the former has already been brought about by the adoption, by the I. E. C., at its Berlin meeting in September, 1913, of certain limits of observable temperature applying to the materials in general use today. But these limits do not offer a means of comparing directly machines from various sources, since they would not necessarily have the same temperature rise. No international decision has yet been arrived at in regard to the value of the cooling-air temperature to be associated with the upper limits already adopted, the commission wisely preferring to adhere to its rule of not taking action on any important question except on a four-fifths majority of the countries registering their votes. The wisdom of this procedure has been amply justified on more than one occasion, and although the advent of the war has unfortunately resulted, in so far as international standardization is concerned, in what might be termed a state of suspended animation, there is every reason to anticipate that the delay thus enforced will not adversely affect the solution of this particular problem.

However, there are very good grounds for hoping that the temperature rise recognized as standard in America and Great Britain will ultimately be accepted throughout the world.

It is evident also that the standardization rules in use in the various countries will tend to grow less divergent in proportion as the work of the I. E. C. progresses, and although the international rules are not intended to supplant those employed locally, they cannot fail, when issued, to be of material assistance to buyers and sellers of all nationalities. In addition to, or rather collaterally with, the rating of machinery, the I. E. C., through properly constituted special committees, has under consideration several other matters which come under the general heading of nomenclature and symbols. The work accomplished, so far, in these directions, may by some, be considered somewhat academical, but it should not be overlooked that international symbols, if widely adopted as they deserve to be, will greatly assist in the reading of foreign technical works, and that international agreement in regard to nomenclature, immensely difficult as it is, and calling for so much personal sacrifice of long-cherished conditions, will be of the greatest value to the industry generally. Also the subject of graphical symbols for electrical plans now being studied will be of considerable assistance in foreign tenders. Experience shows that the utmost caution is necessary in all international questions, and that nothing is to be gained by forcing a vote on a point not yet ripe for decision. One may hope with confidence that when peace reigns once more in distracted Europe, industry will be more than rehabilitated, and the electricians of the world fully appreciating, as they have, the potentialities of such co-operation, will continue their work so well begun.

I cannot close this brief review without paying a tribute of love and respect to the father of the I. E. C., Col. R.E. Crompton, C. B., its Honorary Secretary, to whose enthusiasm and ceaseless energy the commission owes its very inception. He has been a tower of strength at all times, and has ever been ready with the counsel of his ripe experience to help and encourage us through all our vicissitudes. May he long be spared to us!

I should like also to record my appreciation of the invaluable assistance of the American Section of the I. E. C., which the central office has so uninterruptedly enjoyed. To Dr. Mailloux, with his wonderful linguistic ability, we owe a debt it is impossible to repay. In the early stages of the movement, it was owing to the perfect ease with which he was able to explain knotty points in several languages, almost without realizing in which he was speaking, that the many difficulties connected with the launching of such an enterprise were successfully smoothed away. To Dr. Kennelly, too, I owe much for the kindly help and advice he has always so generously given me. Indeed, in times of difficulty, the American Section has never been appealed to in vain.

Laboring thus in the fullest degree for the advancement of the electrical industry of the world, it will be this close co-operation which will win the day, due, not so much to any particular individual, but rather, as Kipling says, "to the everlasting team-work of every blooming soul."

DISCUSSION ON "STANDARDIZATION" (LE MAISTRE) CLEVELAND, OHIO, JUNE 27, 1916.

Clayton H. Sharp: We are, indeed, very fortunate to have Mr. le Maistre with us here today. He has told us something about the work and organization of the Engineering Standards Committee of Great Britain, and of the I. E. C., but, naturally, did not say anything to us about what I might call the real *deus ex machina* of international standardization, and that is Mr. le Maistre himself. If it had not been for his extraordinary genius in diplomacy, in turning the sharp angles, in smoothing down the ruffled feelings, in finding the way out, in working with entire self-effacement, and self-forgetfulness, with the major end in view, if it had not been for the wonderful work on the part of Mr. le Maistre, the success of the entire movement would have been very questionable, indeed.

Those of us who have been to the other side to attend the meetings of the I. E. C. and of its committees, have formed a very great affection for him, and the utmost confidence in his far-sightedness, and above all, in his fair-mindedness. Now that he has come over to this country, the contact between the work of the British Committee of the International Electrotechnical Commission and our own Committee will undoubtedly be established even more closely than before, and we know we have in Mr. le Maistre a thoroughly reliable foreign connection, a go-between, if you please, whereby the concordance of the work in this country with the work in Great Britain will be assured, since he will act to each committee as an interpreter of the work of the other. We, therefore, ought to thank him for coming, and we ought to thank his broad-minded chiefs on the other side who have sent him. I am sure he will go back with the heartiest good wishes of all of us who have met him here.

Farley Osgood: I cannot say too many kind things about our English friend, Mr. le Maistre. He came here a few weeks ago, unknown personally to most of us, although well known by reputation, and he at once was a help to us in our standardization work. His assistance at the Chicago conference of the Bureau of Standards, in connection with the Safety Code, was very great and his clear explanation of the English methods of caring for this kind of work very materially assisted in our discussion at that time, and all felt that we were fortunate to have had a visit from him at this most opportune moment.

C. P. Steinmetz: I have little to add, except to say that as a member the first Standards Committee which was organized here in 1897, and repeated the next year, and as a member of all the succeeding Standards Committees and all the National Electrical Committees, until the last year, when naturally the younger generation, our pupils, took over the work, I have always been very much interested in the work of national and international standardization, though I must confess that when international standardization was started I very much doubted the feasibility of accomplishing many of the results aimed at, due to the difficulty of getting practically unanimous agreement, which was necessary, between all the nations, but I must confess I was greatly surprised by the relatively large amount of work accomplished.

How this was done I have only in the last day or two been able to realize, by having a chance to discuss the matter with Mr. le Maistre, and I then realized that in this work, as in many others, the result was to a very large extent the personal accomplishment of one who devoted all of his time and energy to the purpose.

Mr. le Maistre says that the work of international standardization is now unfortunately in a state of suspended animation; that is true, but during these days the world is being impulsively driven into shape for co-operation, and all standardization is based on co-operation. When this unfortunate war ends, and the nations wake up again, after finding themselves very much changed, the old idea of every one for himself will be seen to have vanished, and there will be a greater realization of the necessity of co-operation for the mutual welfare. We may well imagine that these few days of suspended animation are not lost, but that the work of international standardization will proceed with increasing rapidity and it will more than make up for the lost time, as soon as these present conditions pass.

C. le Maistre: So many kind things have been said of me by so many people that it would take a very long time if I tried to thank each one personally.

My visit here has, I have said repeatedly, been to me an inspiration. I have seen the large way in which you view the problems, I have seen the co-operative spirit so alive here; and as to the kindnesses which have been shown me by everybody, by the manufacturers, the large corporations as well as the smaller manufacturers, who have done so much for my physical comfort as well as for my mental instruction, I can only say I go back to London with a feeling that I really have been accepted as one of your family.

Words are very poor conveyers of thought, and I could not really express to you these feelings of unspeakable gratitude I have for having had the privilege of coming to America and of knowing something of your institutions, and of meeting so many men, so eminent in our profession, but, at the risk of repeating myself, I say that I hope that, at least in some cases, that these friendships will not be like the high-tension spark, but more like the continuous current.

Due to the rapidity with which communications are increasing in proficiency, the world is becoming more and more one nation, and it is by these meetings that we are gradually becoming more highly cosmopolitan in the truest sense of the word. We get our rough edges knocked off and begin to appreciate other people. I am sure my own Committee will appreciate very highly, indeed, the reception which their delegate has received here, and the very substantial co-operation that there has been between our nations.

I can say that I have so many friends here that I do not feel that I can mention one without neglecting a very long list of the others, and therefore, gentlemen, all that I can say is that I thank you very much indeed.

C. A. Adams (communicated after adjournment): Not having been present during Mr. le Maistre's address, I am taking this opportunity of expressing myself on two phases of this subject which are close to my heart.

The first of these has to do with the very broad, one might almost say philosophic, aspect of standardization.

The world is today in the throes of its greatest war. But there are other types of conflict between nations or more often between the various groups within nations, which are always with us, and whose possibilities in the way of producing real human unhappiness and misery are quite as great in the long run as those of a war even of the magnitude of that now in progress.

The more one studies such conflicts the more one becomes convinced that one of the most important causes is the lack of mutual understanding and appreciation as between the various groups involved. This lack of understanding is in turn due to the various barriers which separate the groups, and one of the greatest of these barriers is the lack of a common and accurately understood language, this last word being employed in its broadest possible sense. For example, contemplate the large number of disputes based upon different interpretations of the same document, even when the document has been drawn by experts with the greatest care, and with the special aim of avoiding vagueness. How much more difficult it is to avoid misunderstanding between two groups having widely differing life experiences, customs and standards, or again between peoples of different traditions and speaking different tongues.

One of the most important functions of any Standards Committee is to establish within its own field just such a precise and compact language which will be acceptable to all concerned, *e.g.* it is obviously of the utmost importance that we all understand the same thing, when we say that an alternator has a continuous rating of 1000 kv-a. Yet it took your Standards Committee many years to produce a satisfactory and generally acceptable definition of "Rating", and a considerable part of our present rules is devoted to the defining and elucidating of this one word and to explaining how the rating of a machine can be checked by test.

The process by which this result was obtained is in a large degree typical of all the work in this field, and at the same time illustrative of the chief point of these remarks.

First the various groups involved were brought together; they exchanged data, experiences, theories and points of view; until apparent conflicts of interests disappeared through a process (sometimes stormy) of mutual education. In other words they finally came to an understanding through the evolution of a common language. That this language is still imperfect is obvious, but it serves a very useful purpose even now, and will doubtless grow in usefulness as it slowly evolves.

Taking the next step, into the international realm of engineering standardization, we find the same process at work; and although a little more slowly, yet to the same end; a gradual evolution of an international understanding, a substantially universal language, and a cordial spirit of co-operation, which if it extended only to the confines of the particular realm of human endeavor here under discussion, would nevertheless be an important factor in the hastening of that time when the term "human brotherhood" will apply beyond the borders of each particular little group.

To be sure this international movement appears to be temporarily arrested in certain quarters, but I for one, am confident that the engineers of the waring nations will be among the first to set aside partisan feelings for a broader common sense spirit of co-operation.

This brings me to my second point, which is the personal one. In all of this work where representatives of the various groups get together, the personal element is a most vitally important one. One needs the courage of his convictions, but the narrow minded partisan must in the long run give way to the broader co-operative spirit. Many of the chasms of unfriendly misunderstanding which develop in all fields of endeavor might easily be bridged if there were more of this spirit abroad.

In this connection I cannot refrain from adding my tribute to Mr. le Maistre. He came to us as delegate of the Engineering Standards Committee of Great Britain; he sat with us in informal conference or in formal meeting day and night in several periods aggregating two solid weeks; he presented the suggestions of the British Committee in the broadest possible spirit, but did not confine his discussions to that part of the subject; he entered into the spirit of our meetings and became one of us, giving us generously of his time and experience; his personal assistance was of such an order that we shall hereafter feel any revision of our rules incomplete without his suggestions.

This is the kind of getting together, of co-operation, of learning each others' language, of building up a friendly understanding as contrasted with an unfriendly suspicion, which was referred to in the first part of these remarks. It is work of this kind which breaks down the barrier of misunderstanding, and draws groups and nations closer together.

The engineering profession, not only in Great Britain but the world over, is thus to be congratulated in the recent appointment of Mr. le Maistre as General Secretary of the Engineering Standards Committee of Great Britain, and the electrical engineering profession is to be specially congratulated in still retaining his services as General Secretary of the International Electrotechnical Commission.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 27, 1916.

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ELECTRIC DRIVE FOR REVERSING ROLLING MILLS

BY WILFRED SYKES AND DAVID HALL

ABSTRACT OF PAPER

The manner in which the electrically driven reversing rolling mill has been adopted especially within the last year, is surprising in view of the strongly entrenched position of the steam driven mill. Electric motors have been used for many years on mills running continuously in one direction, but many motor users have felt that the reversing mill could be better handled with the steam engine. There are naturally many characteristics little understood, due to the limited use in this country today.

This paper answers some of the questions which are raised and describes the constructions that have been found desirable.

THE ELECTRICALLY driven reversing mill has been the subject of a number of papers* before the Institute in which the general scheme of operation has been described in detail. Since these papers were presented this type of mill has been considerably developed and a number of installations made. In addition, a great many new mills are being equipped, and within the next year there will be 15 reversing mills in operation in the United States. The great success that has been attained appears to warrant a review of this subject together with a discussion of some of the characteristics of this equipment.

Since the first installations were made and mill engineers have been in a position to personally check the operation and economy of equipment, the steam engine for reversing mills has been comparatively neglected. As an indication of the position that the electrically driven mill has attained, the engineers of one of the large steel companies upon making investigation regarding the type of drive to install for new reversing mills, stated that the electric drive would undoubtedly in the very near future entirely supplant the reversing steam engine except in perhaps certain peculiar cases. Practically all the new installations of reversing mills contemplated at present will be electrically driven. Although the electrically driven mill has not so far made the advance in this country that it has in Europe, it is characteristic of American practise to quickly adopt any device which has been demonstrated to suit the American conditions. The reversing mill as developed in this country and as shown by the existing successful installations, differs in many respects from European construction. Special attention has been given to the mechanical construction of the reversing motor and every care has been taken to insure that the machine will stand the much rougher handling which it receives in this country.

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*Electrically Driven Reversing Mills, by Wilfred Sykes. A. I. E. E. TRANSACTIONS, 1911.

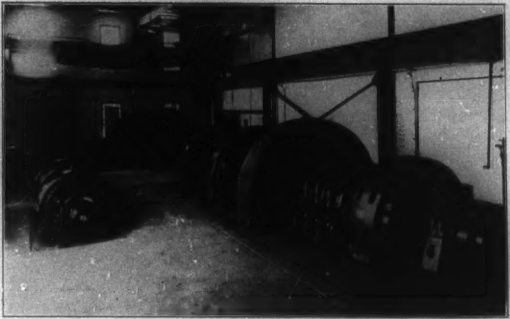
Operation of a Large Electrically Driven Reversing Mill. By Wilfred Sykes, A. I. E. E. TRANSACTIONS, 1912.

Electrification of a Reversing Rolling Mill of the Algoma Steel Co. By B. T. McCormick, A. I. E. E. TRANSACTIONS, 1912.

As pointed out in one of the papers previously read before the Institute, the reversing plate-mill drive installed at the South Chicago plant of the Illinios Steel Co. was the second drive of this type to be put into operation in the world and it was designed without knowledge of the fact that a similar arrangement was being constructed in Europe. It was a number of years later before a reversing blooming mill was electrified.

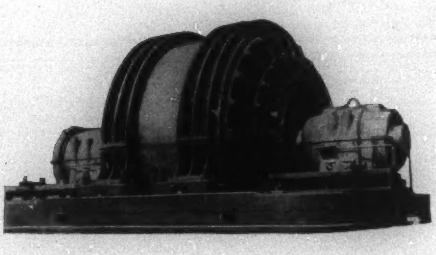
The first successful installation of a reversing blooming mill was that of the Steel Company of Canada at Hamilton, Ont. This installation consists of a double reversing motor capable of developing about 10,000 h.p. maximum, and is supplied with power from a flywheel motor-generator set with two generators. The complete electrical installation is shown in Fig. 1. This mill has been in operation for over three years with very satisfactory results. It is at present working at a rate very considerably in excess of the capacity specified when it was installed. The following are particulars of the mill and driving equipment.

Size of ingot	15 by 17 in.
Weight	4000 lb.
Finished material	4 by 4 in.
Elongation	16
Number of passes	19
Capacity, tons per hour	60
Roll diameter	30 in.
Pinion diameter	34 in.
Speed, full motor field	70 rev. per min.
Speed, weakened motor field	100 rev. per min.
Driven from motor	direct
Number of motors	2
Voltage across each armature	600
Maximum operating torque	900,000 ft-lb.
Maximum motor horse power	10,000
Number of generators	2
Rated power of driving motor of set	1800 h.p.
Weight of flywheel	100,000 lb.
Speed of flywheel set	500 rev. per min.



[SYKES]

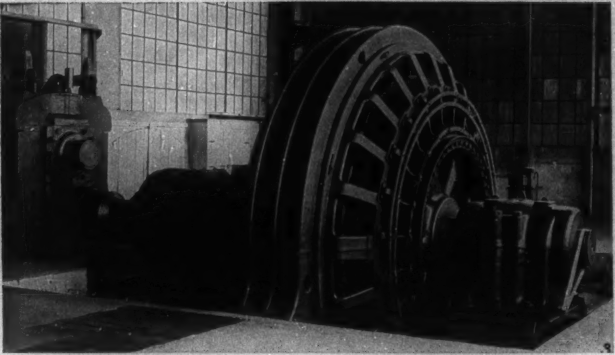
FIG. 1—GENERAL VIEW OF FLYWHEEL MOTOR GENERATOR AND REVERSING MOTOR INSTALLED AT THE PLANT OF THE STEEL COMPANY OF CANADA.



[SYKES]

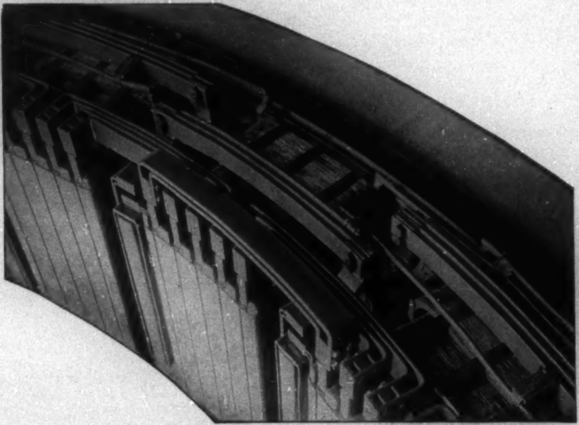
FIG. 2—REVERSING MOTOR BUILT FOR BETHLEHEM STEEL COMPANY ASSEMBLED IN SHOP.

PLATE XIII.
A. I. E. E.
VOL. XXXV, 1916



[SYKES]

FIG. 4—REVERSING MOTOR DRIVING BLOOMING MILL OF CENTRAL STEEL COMPANY



[SYKES]

FIG. 12—COMPENSATING AND COMMUTATING POLE WINDINGS AS USED IN REVERSING MILL MOTORS

The largest installation at present in operation is that of the Bethlehem Steel Co. which drives the 35-in. blooming mill at the Lehigh Plant. Fig. 2 shows the motors as assembled in the shop before shipment. Both of the above mentioned installations have double motors due to the amount of power required. The machines are arranged as shown by diagram, Fig. 3. A somewhat similar drive is installed at the plant of the Central Steel Co., Massillon, O., but a single motor is used for driving the mill, the capacity of the motor being approximately 8000 h.p

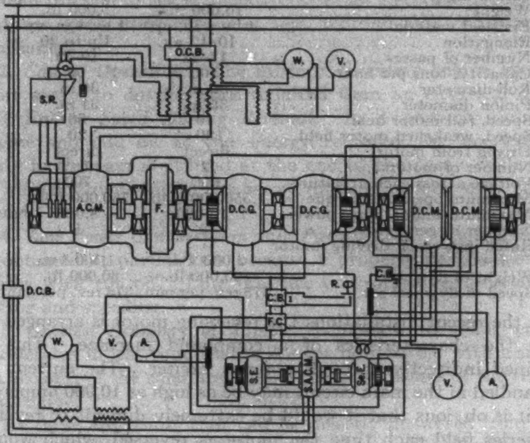


FIG. 3—SCHEMATIC DIAGRAM OF CONNECTIONS OF LARGE REVERSING MILL DRIVE

OCB	—oil circuit breaker with no-voltage and overload trip
SR	—automatic liquid slip regulator
ACM	—alternating-current wound-rotor induction motor
DCG	—direct-current separately-excited generators
DCM	—direct-current separately-excited roll motors
CB	—circuit breakers—1 generator field—2 main circuit
R	—relay for operating circuit breaker in generator fields
FC	—field controller
F	—flywheel
SE	—shunt exciter for generator and roll motor fields
SeE	—roll motor exciter the field of which is separately excited by the main d-c. circuit
SACM	—alternating-current squirrel-cage induction motor
V	—voltmeter
A	—ammeter
W	—wattmeter

This motor is shown in Fig. 4, which illustrates the machine as installed for driving the mill. Characteristics of these mills are as follows:

	Bethlehem Steel Co.	Central Steel Co.
Size of ingot	19 by 23 in.	18 by 20 in.
Weight	10,000 lb.	5,000 lb.
Finished material	4 by 4 in. up	4 by 4 in. up
Elongation	10–12 av.	Up to 20
Number of passes	17–21	19–21
Capacity, tons per hour	100	60
Roll diameter	30 in.	30 in.
Pinion diameter	35 in.	34 in.
Speed, full motor field	40	50
Speed, weakened motor field	120	120
Driven from motor	direct	direct
Number of motors	2	1
Voltage across each armature	600	700
Maximum operating torque	1,550,000 ft-lb.	750,000 ft-lb.
Maximum motor horse power	12,000	8,000
Number of generators	2	1
Rated power of driving motor of set	2,000 kw.	1,500 kw.
Weight of flywheel	100,000 lb.	60,000 lb.
Speed of flywheel set	375 rev. per min.	375 rev. per min.

In the recent installations the reversing motor is arranged to have the characteristics of a compound machine. This is obtained indirectly through a series exciter. The current to be handled in the main circuit may be as high as 10,000 amperes, and it is obvious that it would be extremely difficult to reverse the series field each time the motor is reversed, which would be necessary to keep both fields in the same direction. A series exciter is therefore used, the voltage of which is proportional to the current flowing in the main circuit. The armature circuit of the series machine supplies a separate winding of the field of the motor which may be readily reversed when the direction of rotation current is changed. The switches for reversing this field are operated from the same point on the master switch that reverses the field of the generator. The use of a motor with compound characteristics makes the operation of the mill a good deal easier on the mechanical equipment as the drive has more or less "give" to it. At the same time if there is an extreme load due to excessive draft or cold steel, the motor characteristics tend to compensate by automatically increasing the torque available and decreasing the speed.

Although the electrically-driven reversing mill has been practically adopted universally for all new installations there is still some misapprehension as to its operating characteristics.

It is of course natural that engine builders will fight the development of the electric reversing mill drive as much as possible and the following advantages have been claimed by one of the prominent engine builders:

1 *First Cost.* The first cost of the reversing engine is only a small fraction of the aggregate cost of an electric drive (steam turbines, generators, converter sets, motors, field controls and auxiliaries).

2. *Cost of Operation.* The modern reversing engine uses no more steam to do the work required than an electrical drive.

3. *Energy Saved During Reversal.* In a properly designed engine and mill *all* of the energy required for acceleration early in the pass is utilized at the end of the pass; while with an electric drive, due to the heavy rotating masses, only part is saved.

4. *Low Power Consumption with Partial Load.* High economy is obtained at partial load because a properly designed engine works with cut off. Low pressure control valves prevent all racing and speeding.

5. *Greatest Economy of Time.* A modern reversing engine accelerates in less time than will ever be possible with a motor on account of the smallness of the rotating masses of the reversing engine."

As these are points that can be directly answered from data already available on electrically driven reversing mills in the United States, the points are taken up in the order given.

1. The first cost of an installation does not consist only of the cost of the engine or of the motor driving the mill. In the case of steam drive there are a great many items to be considered which include boiler plant, coal and ash handling facilities, coal storage yards, steam piping, condensing system, water supply for the condensing system, and foundations. In the case of electric drive in addition to the reversing motor there is the flywheel motor-generator set to supply power to it and the generating equipment consisting of power house with its complete equipment, or if power is purchased the only items to be considered are the motor-generator set, reversing motor and the small amount of control apparatus. Many of the items entering into the cost of the drive depend upon the particular layout of the plant. For, instance the whole plant layout might have to be modified so as to enable boilers to be located within a reasonable distance of the steam consuming engines, and this

very often seriously restricts the arrangement of the mills and other units. It may cost a very considerable amount of money to supply water to the engine condensers, which must be used if reasonable economy is desired, whereas in the case of generating station it would naturally be located close to the water supply. This would also be the natural location if blast furnaces are installed, as in this case the boilers would be close to the blast furnaces and the blast furnaces will of course be close to the dock on which the ore is unloaded, if water transportation is used. In any case the blast furnaces would be located close to the water supply which is also desirable for the boilers. It is of course immaterial from the distribution standpoint where the generating equipment is located. This is not so with the steam driven plant due to the length of piping and the consequent losses. The statement that the first cost the reversing engine is only a small fraction of the aggregate cost of an electric drive is certainly not correct as will be shown by the following figures. These figures are based on the actual installation cost and while some of the items would undoubtedly have to be modified to suit different locations, these figures give some idea of relative costs of the equipments.

COST OF EQUIPMENT FOR DRIVING 40-IN. BLOOMING MILL TO ROLL 60,000 TONS OF STEEL PER MONTH, 24 BY 24 TO 8 BY 8 IN.

Electric drive with purchased power.	
Complete cost of reversing motor, flywheel motor generator set, exciters and control equipment	$185,000
Foundations, wiring, etc	10,000
Total	$195,000
Electric drive with power generated at plant.	
Complete cost of reversing motor, flywheel motor generator set, exciters, and control equipment	$185,000
Foundations, wiring, etc	10,000
Proportion of power house cost, 2500 kw. at $50 per kw	125,000
Transmission and outside wiring	5,000
Total	$325,000
Steam Drive.	
Compound reversing engine	$125,000
Condenser, exhaust piping, including pumps	25,000
Foundations	10,000
Boilers, 2500 h.p., including stokers, coal and ash handling plant at $30 per h.p.	75,000
Steam piping with covering, valves, etc	15,000
Water tunnel for condenser with discharge 8500 gallons of water per minute	50,000
	$300,000

2. The statement that the modern reversing engine uses no more steam than the electric drive indicates the lack of knowledge of what the electric drive requires. So that there can be no misunderstanding on this point, in Tables I and II are produced the figures from a paper read before the Engineers Society of Western Penna. by Mr. Karl Nibecker giving the results of tests on a reversing engine. This engine is one of the most modern installed in the United States and comparison between it and the electrically driven mill can be justly made. It will be noted

TABLE I.—STEAM CONSUMPTION OF REVERSING STEAM DRIVEN BLOOMING MILL

POUNDS OF STEAM PER TON

No.	Size		Elongations	Lb. steam per ton	Remarks
	Ingot	Bloom			
A	20 by 22 in.	7 by 6 in.	9.04	587	Cold ingot
B	20 " 22 in.	7 " 6 in.	9.04	490	Hot ingot
C	20 " 22 in.	7 " 6 in.	9.04	497	Good rolling
D	20 " 22 in.	7 " 6 in.	9.04	520	New engineer
E	20 " 22 in.	7 " 6 in.	9.04	518	New engineer
F	20 " 22 in.	7 " 6 in.	9.04	575	Bad rolling
G	20 " 22 in.	7¾ " 3½ in.	15.1	767	New engineer.
H	20 " 22 in.	7¾ " 3½ in.	15.1	610	Good manipulation
I	20 " 22 in.	11¾ " 3 in.	10.75	694	New engineer
J	20 " 22 in.	11¾ " 3 in.	10.75	625	Good manipulation
K	18 " 32 in.	23¾ " 4¼ in.	5.13	522	Good rolling-cold
L	18 " 32 in.	23¾ " 4¼ in.	5.13	423	Good rolling-hot
M	19 " 46 in.	36¼ " 4½ in.	4.63	356	Bad rolling
N	19 " 46 in.	36¼ " 4½ in.	4.63	292	Good rolling

TABLE II.—STEAM CONSUMPTION OF REVERSING STEAM DRIVEN BLOOMING MILL

Size		Number of elongations	Lb. steam per ton	Lb. steam per ton at	
Ingot	Bloom			5-Elong.	9-Elong.
20 by 22 in.	11¾ by 3 in.	11.5	643	444	591
20 " 22 in.	7¾ " 3½ in.	15.0	600	375	505
20 " 22 in.	7 " 6 in.	9.0	495	350	495
18 " 32 in.	23¾ " 4¼ in.	5.0	420	420	....
16 " 32 in.	29 " 5 in.	3.25	280	...	....
19 " 46 in.	36¼ " 4½ in.	4.75	300	...	....
18 " 32 in.	23¾ " 3 in.	7.5	410	256	....

that these are tests of single ingots, but Table I shows the results of a series of six ingots rolled from the same size bloom from which a fair average can be obtained. Table III gives the results of tests made upon electrically driven reversing mills which are shown graphically in Fig. 5. These figures are not the results of tests of individual ingots but are based upon the power consumption of a large number of ingots rolled during the regular operation of the mill and they do not in any way represent figures made under ideal test conditions. They have been obtained by reading the watt-hour meter in the line supplying power to the reversing mill equipment including all losses and represent the total power required to drive the mill. Fig. 6 shows the steam consumption of a 5000-kw. turbine, which is a common size in steel mills, operating under the same steam conditions as the steam-driven reversing mill. These steam conditions are not altogether ideal for a turbine as a higher pressure and superheat might be used, in which case still lower

TABLE III.

ELECTRICALLY DRIVEN REVERSING MILL.

Ingot	Bloom	Elongation	h.p-hr. per ton.	Remarks
18 in. round	7¾ by 7¾ in.	4.66	11.4	High carbon
18 by 20 in.	3 " 8 in.	12.2	23	" "
18 " 20 in.	2 " 16 in.	9.2	19.4	Soft steel
18 " 20 in.	4 " 4 in.	18.5	26	
17 " 15 in.	4 " 4 in.	16.	24	
20 " 20 in.	5 " 5 in.	16.	25.5	
20 " 20 in.	8 " 8 in.	6.25	17.	

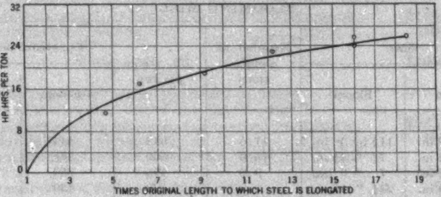


FIG. 5—CURVE SHOWING RELATIONS BETWEEN INPUT TO ELECTRIC DRIVEN REVERSING MILL AND ELONGATION OF STEEL ROLLED

steam consumption and better thermal efficiencies would be obtained. This curve of steam consumption includes the power necessary to operate the condenser circulating water pump and the air pump. Under normal operating conditions the turbine would run at 70 per cent of load and taking the steam consumption at this point, we find that one h.p-hr. can be generated for 13.6 lb. of steam. From the power requirement the total steam consumption can be calculated and it will be seen that this does not amount to more than from 50 per cent to 60 per cent of the best engines installed in the United States to date.

3. The question of saving accelerating energy is one that is given a good deal of thought by the engine builders as there is no way of storing it in the engine. The characteristics of the motor and engine are entirely different. It is true that if a mill is operated in an ideal manner the metal will leave the rolls at practically zero speed so that all the energy stored in the rotating parts will have been returned to the mill and usefully consumed. Mills, however, are not operated in this way and neither the electric drive or the engine drive is operated in an ideal manner. Mills are handled by workmen and not by designers, and production is the object arrived at. The workmen are not interested nor do I believe it is possible to interest them, in the best conditions for obtaining low power consumption. This is a condition that must be reckoned with, and if possible the design of the equipment should be such that the power consumption cannot be affected materially by unskillful operation.

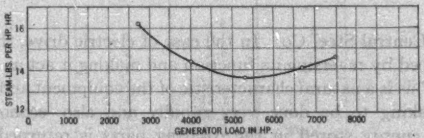


FIG. 6—STEAM CONSUMPTION OF 5000-KW. TURBINE, 150 LBS. STEAM PRESSURE, 28-IN. VACUUM

Due to the fact that the speed of the reversing motor is proportional to the throw of the controller handle and does not vary appreciably with the load, ideal conditions can be more nearly approached than with a steam engine. In the case of steam drive, it is quite common for the engine to race after the metal has left the rolls, especially if the draft has been a heavy one, when there may be a large volume of steam in the cylinders which is not expanded, and which accelerates the engine parts. The engine must then be stopped and energy is required to do it. Fig. 7 shows the speed curve of a reversing engine taken from a recent test. It will be seen that in quite a number of cases the engine has raced after the metal leaves the rolls. For comparison a similar speed curve is reproduced of an electrically driven mill taken from the motor at the plant of the Central Steel Co. In the case of electric drive, the motor is stopped by reversing its function and making it act as a generator. This is a natural characteristic of the equipment and enables the braking to be done very rapidly and also economically, as the energy stored in the rotating parts is returned to the flywheel of the set. The losses are only those due to the resistance of the windings. Whatever energy might therefore be lost due to the fact that the mill is not operated in an ideal manner is returned to the flywheel and is available for the next pass. The whole point, however, is of little importance as it shows up in the relative power consumption of the two methods of drive which after all is the only criterion as to which is the better system to use.

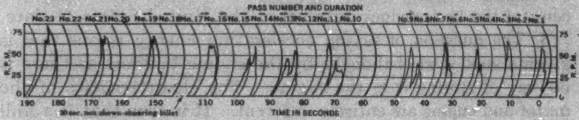


FIG. 7—SPEED CURVE OF REVERSING ENGINE. (*Note:* ONLY ALTERNATE PASSES SHOWN TO OBTAIN LARGE DEFLECTION ON RECORDING INSTRUMENT.)

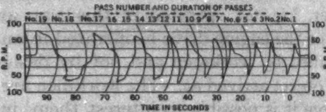


FIG. 8—SPEED CURVE OF REVERSING MOTOR DRIVING MILL

4. With electrically driven mill the economy of course falls off somewhat as the output is reduced due to the continuous windage and friction losses of the flywheel motor-generator

set which are independent of the load on the machine. Outside of these losses it makes practically no difference whether one or 30 ingots are rolled per hour as far as the unit power consumption is concerned. In other words, the net power, (leaving out the constant losses) per ton of steel is practically independent of the quantity rolled. A somewhat similar condition exists with the steam engine inasmuch as it has certain constant losses due to leakage, piping and auxiliary power. However, outside of these losses the steam consumption will not be constant per unit of work done as the expansion conditions vary.

TABLE IV.
TIME STUDY OF REVERSING ENGINE

Pass No.	Time of entering pass-sec.	Manipulation
1	0.	
2	3.5	
3	9.7	Turn
4	13.	
5	17.2	
6	20.8	
7	27.2	Turn
8	31.8	
9	37.0	Turn
10	42.0	
11	50.0	Turn
12	55.0	
13	62.0	Turn
14	67.7	
15	75.8	Turn
Leaving press	79.3	

5. The question of the time required for operation is liable to be clouded very much by conditions that have nothing whatever to do with the time required for rolling the metal. It is undoubtedly true that the steam engine can reach certain given speeds quicker than the reversing motor. At the same time it does not necessarily follow that the reversing engine will roll any greater amount of metal than the reversing motor. It depends upon many other conditions such as the way the metal is handled on the tables, the maximum speed reached, and also time lost in the manipulation of the driving unit. Table IV shows the results of a time study brought out in a discussion

of the paper already referred to. Table V shows the results of similar figures taken from the reversing motor on the Central Steel Co. plant at Massillon, O. It will be seen that the time of entering the 15th pass in the case of the steam-driven mill was 75.8 seconds from the beginning of rolling and in the case of the motor driven mill 59.8 seconds. While it is not claimed that these figures show the advantages of one over the other system of drive yet they are sufficient to indicate that in practise the reversing motor will operate just as quick, if not quicker than the engine. Due to the ease of control, the motor drive is a good deal lighter on the operator and consequently he is able to continue running the mill at a maximum capacity with less fatigue than in the case of a steam-driven mill.

TABLE V.

TIME STUDY OF REVERSING MOTOR

Pass No.	Duration of pass	Interval after pass	Time of entering pass integrated	Rev. per min. at entrance of ingot	Maximum rev. per min.	Rev. per min. as ingot leaves rolls
1	1.5	1.7	0	15.5	39	26.5
2	1.2	5.	3.2	36	47	31 *
3	1.7	1.6	9.4	12.5	47	28
4	1.4	1.5	12.7	23	48	27.5
5	1.7	1.4	15.6	7.8	44	20
6	1.7	5.5	18.8	23.5	55	31 *
7	2.0	1.2	26	11	50	18.5
8	2.0	0.6	29.2	23.5	62	12.5
9	2.5	1.4	31.8	15.5	56	31
10	2.2	3.7	35.7	23.5	59	31 *
11	2.5	0.8	41.4	18.5	55	14
12	2.6	1.2	44.7	23.5	78	31
13	2.9	2.0	48.5	23.5	62	34
14	2.6	3.8	53.4	28	67	51 *
15	2.8	2.0	59.8	7.8	64	31
16	3.0	4.2	64.6	15.5	76	55 *
17	5.0	4.2	71.8	23.5	74	31
18	5.0	5.0	81	23.5	70	62 *
19	6.5	2.5	91	22	80	12.5

* Piece manipulated.

Rolling 18 by 20 in. Ingot to 3 by 8 in. sheet bar blooms.

The design of the reversing motors and the generators supplying them with power presents many problems not encountered with ordinary direct-current machines. As the success of this type of mill depends upon the machines meeting the severe operating conditions without injury or deterioration, a brief review of the principal characteristics may be of interest.

There is no other class of service which might be properly compared with the requirements of a large reversing mill. The heavy torques, the sudden peak loads, and the quick reversals all call for apparatus of substantial mechanical design, and flexibility in electrical characteristics. The exchange of energy between the driving motor and the generator undergoes changes at a very rapid rate. In fact, the driving motor must perform the functions of a generator as well as that of a motor, and the supply generator may at one instant be furnishing current to the driving motor, and at the next instant it may be receiving electrical energy from the driving motor, and delivering mechanical energy to the flywheel. For example, the equipment at Bethlehem, which consists of two 600-volt motor armatures supplied by two 600-volt generator armatures all connected in series, may at one instant show a swing of 10,000 amperes, and at the next instant the swing may be of an equal value in the opposite direction. There must be rapid adjustments of flux conditions in both motors and generators in order to meet these reversals without showing harmful sparking at the brushes, and as the swings which occur many times a minute represent over-loads of 200 to 300 per cent, the design of the direct-current machines must be suited to these overloads, both in current carrying capacity and in flux conditions. Especially must the machines be designed for good commutation. This cannot be obtained at such overloads without making liberal allowances for the commutating flux, as the ratio which the commutating flux bears to the load must not be disturbed by leakage conditions, even at the overloads. This feature is more readily obtained by compensating the armature reactance to which further reference will be made, and this type of construction is of greatest importance, to successful results.

The choice of voltage per commutator and the use of two armatures, the commutators of which are connected in series for large powers, is deserving of a careful analysis, and this voltage should be selected with due consideration of the motor, the generator and the auxiliary apparatus. The following arguments are to show that, other things equal, it is desirable to adopt a relatively high voltage; viz. 600 volts and by series connection, alternating a motor with generator, derive all the benefits of 1200 volts.

The electrical equipment of a reversing rolling mill includes both the d-c. generator as well as the d-c. motor, and the generator does not furnish power to any other apparatus except the roll mill motor. The *voltage* should be of such a value as will give the best balanced equipments and the choice of voltage becomes a very important factor as the design of the entire equipment may be said to depend in a great measure upon the voltage selected.

The use of 250 volts has been common practise in rolling mills and it is natural that this voltage should be considered. However, for large capacities, there are many objections to so low a voltage, among which may be mentioned heavy currents, large commutators, larger machines, lower efficiencies, increased cost of auxiliary apparatus, higher maintenance charges and increased mechanical difficulties.

The magnitude of the current becomes a factor when the power required on peak loads may reach 15,000 to 20,000 h.p., and not only are the connections, cables and switching apparatus expensive, but the losses in these parts are roughly proportional to the currents. The approximate cost of these parts will vary inversely as the voltage.

The size of commutators and the number of brushes will be a direct function of the current and it is desirable to keep down the size of the commutators from at least three points of view —mechanical difficulties of construction, over-all length and cost. No part of a direct-current machine is so difficult to construct as is the commutator, and for this reason the construction of commutators has received, and will continue to receive the most careful consideration from both the design and the manufacturing points of view. So all important is the commutator and the commutation that when these are right, there is seldom any cause for complaint. Increased voltage not only reduces commutator length, but insures less overall length—an extremely desirable factor.

The efficiency of the equipment as a whole will be higher with increase of voltage within certain limits, as in such installations the peak loads are relatively high as compared with the average or mean load.

The commutating condition of the generator is one of the items which must be carefully considered in the selection of voltage, especially as economies can be effected by operating the flywheel set at a reasonably high speed. It is desired to consider whether a generator can be designed better for one voltage than for another, and what is a safe operating speed for a generator of a given output and voltage. With a view of setting forth the relations of kilowatt capacity and speeds, the writer has chosen familiar voltages of 125, 250, 600, 1200 and 2500 volts, and has plotted a curve for each one of these voltages. These curves are shown in Fig. 9. There are certain fairly well established relations and limits in direct-current machines, which lead to limits of output. However, it is not so much these limits that we would direct attention to at the present moment, but the relation of possible outputs of different voltages. It will be observed that at 600 volts the possible outputs are greater than at either 250 volts or 1200 volts. This means that with the same degree of safety it is possible to make a larger 600-volt generator than a 250-volt or 1200-volt generator, for a given speed. This relation applies at all speeds. It will be observed that the product of kilowatt output and rev. per min. is approximately a constant for a given voltage. This relation is frequently lost sight of in considering the possibilities of machines for large output, at high speed. The basis on which these curves have been made up depends upon setting certain limits. These limits are not definitely fixed quantities, as each designer will set limits depending upon the experience which he has had with various machines. The relation of these limits will in a measure determine which curve will be highest, and some of these limits are entirely independent of each other. The limits which determine the possibilities of high-voltage machines are entirely different from those which determine the possibilities in low-voltage machines. Curves could be drawn for all voltages in

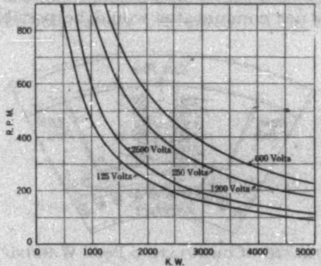


FIG. 9—CURVE SHOWING THE LIMITS WITHIN WHICH DIRECT-CURRENT GENERATORS CAN BE BUILT

a similar manner as these have been determined, but the more usual voltages are used for the sake of illustration, and they serve the purpose of showing the desirability of using a relatively high voltage for roll mill motors, such as we are considering.

As these curves represent limits it is of course understood that most machines will fall under them and the extent to which a machine falls within the curve will represent in a measure the ease with which that machine can be designed. We would emphasize the fact that the minimum cost for a given rating does not necessarily call for the highest possible speed, and the present day tendency of going to extreme speeds should be discouraged.

From these curves we deduce that 600 volts is a desirable selection per commutator for the generators and it is also evident that 1200 volts per commutator would be possible. A voltage of 600 per commutator has proven well suited for the motor, as a lower voltage would lead to relatively large armature diameter. A very much higher voltage would require few poles with correspondingly heavy rotors, and either of the conditions is undesirable as low inertia effect is important.

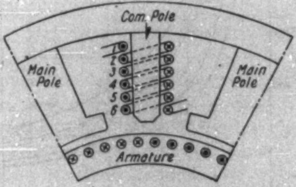


FIG. 10—COMMUTATING POLE WINDING

TYPE OF WINDING

To obtain the best operation under heavy peak loads, which are subject to very rapid changes, for example, three times normal load, reversing at the rate of 30 times a minute, it is not only desirable, but it is necessary to neutralize to the fullest extent the distorting effects of the currents in the armature winding. The method of obtaining this result is to slot the pole face, and secure in these slots a bar winding which is connected in series with the armature, and making a number of conductors in the pole face just sufficient to neutralize the armature conductors covered by the pole face. The excess winding necessary to produce a commutating flux is concentrated on the commutating poles, located midway between the main poles. The difference between the compensating winding and the interpole winding is illustrated in Figs. 10 and 11, which show the same number of conductors in both cases, but the conductors are shifted in position. In the plain commutating-pole machine, having all the commutating winding located on the commutating pole, the conductors are as shown in Fig. 10, whereas in the compensating pole machine, which has part of the compensating winding located in the main pole face and the balance located on the commutating pole, the conductors are as shown in Fig. 11. By locating in the pole face the ampere conductors which neutralize the armature reaction under the pole face, the distortion of the flux at the main pole face is prevented. This has a beneficial effect in two ways. First, it prevents under sudden changes of load, a sweeping across the pole face of the main flux under the pole, and it prevents a distortion of the main flux which is a very important consideration, as this lowers the maximum voltage between adjacent commutator bars, which would otherwise obtain. As it is the maximum voltage between commutator bars, rather than the average voltage, which determines the design, the importance of this type of construction becomes evident for this class of service. Another very important consideration in this arrangement of the compensating winding is that the leakage from the commutating pole is very much less than would be the case if all of the windings were concentrated on the interpole. This fact permits the carrying of heavier overloads, and it is the overload capacity which determines to a great extent the suitability of machines for this class of service. It is evident that the leakage is very much reduced, when one

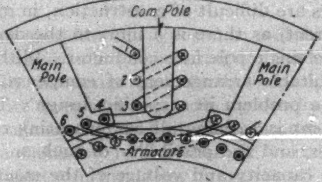


FIG. 11—COMMUTATING POLE AND COMPENSATING WINDING

considers that the leakage is mainly between the main pole tip and the interpole, and that the magnetomotive force producing this leakage is made very much less by locating a large proportion of the ampere conductors in the main pole face.

This construction permits the operation of the machines through a wide range of voltage; in other words, the stability of the main flux is insured without regard to the strength of the main field winding. This is an important factor in the general scheme of control, as the speed of the motor and the direction of rotation of the motor depend upon the generator voltage and upon the field strength of the motor. These two factors must be susceptible to rapid changes and wide variations in order to effect the desired result.

In referring to the relative merits of commutating pole machines, versus machines with compensating winding, for this class of service, attention may be called to the fact that compensating windings are difficult of construction, in machines having very large current, as there is a limit to the desirable physical dimensions of a single pole face conductor. With heavy current machines, a suitable arrangement of compensating conductors is often quite a problem in a specific design. The most desirable arrangement is to have all compensating conductors connected in series, and the possibility of such an arrangement is limited by the capacity and voltage of the machine, and here again there is a decided advantage in not having the voltage too low, for large power capacities. For example, a single conductor having a cross section of more than two sq. in., is seldom used in the pole face winding. Assuming a current density of 1500 amperes, a single conductor, with all conductors in series, can be used on a 3000-ampere machine, which, at 600 volts, represents an 1800-kw. capacity. For larger current capacities, it is necessary to connect the conductors in parallel, and frequently the circuits are in parallel. In such cases, great care must be exercised in the building of the machines so as to have good joints, in order to insure the proper division of the current.

Generally speaking, the compensating winding of large capacity machines consists of a relatively small number of conductors, and simpler, better mechanical arrangements can be effected than are possible with smaller capacity machines. It is also desirable to design the compensating winding and the commutating pole winding so that no shunts will be necessary. This can readily be accomplished as it is possible to calculate very closely the required ampere conductors, for compensating the armature reaction and furnishing the necessary excitation for the commutating pole. By avoiding shunts, one is insured of the simultaneous change of current in the compensating winding and the armature winding.

FIELD WINDINGS

The type of field winding used on roll mill machines should be very simple, and such as not to be easily damaged. If a low voltage is used for excitation of the d-c. generator and d-c. motor field coils, these coils can be made of copper strap winding with a layer of asbestos between turns, and the bare edges exposed to the air. Such coils are almost indestructible by heat. Strap wound field coils arranged in two or more concentric sections insure a natural and easy ventilation.

INSULATION

As this type of machinery is exposed to mill dust, and as this dust is likely to contain a large percentage of conducting material it is advisable in the design to embody more liberal creepage distances than are necessary for ordinary service. In order to combat, to a certain extent, the bad effects of dust, the armatures may be given a finish by rolling them in varnish and baking them. This produces an insulating film over all parts, and fills all the pores and small crevices in the insulation, and insures a slick finish which will shed the dust.

DISCUSSION ON "ELECTRIC DRIVE FOR REVERSING ROLLING MILLS" (WILFRED SYKES AND DAVID HALL), CLEVELAND, OHIO, JUNE 27, 1916.

K. A. Pauly: There are several points in connection with this paper by Messrs. Sykes and Hall to which I wish to refer in discussion. One of the first points which is worthy of attention is that of the rating given these motors: namely, a horse power corresponding to the maximum torque which they will carry without any mention of the time during which they will carry the load. All will agree that a rating on this basis is not only contrary to the recommendations of the A. I. E. E., but is very unsafe for the purchaser on which to base the relative capacities of competitive equipments for any class of service. That the idea of so rating these motors is a new one will become apparent to any one examining the publications of the company with which the authors are connected. The early publications showed, for example, 3000 h.p. as the capacity for the motors of the Steel Company of Canada now rated at 10,000 h.p. On this same basis, any one of the 6000-h.p. motors at the Gary Works of the Illinois Steel Company might be rated at 20,000 h.p.

As to the relative merits of the electrically driven reversing mill and its steam competitor, it is difficult to discuss a question of this magnitude in generalities, because there are so many factors affecting the problem, which are more or less important, depending upon the special conditions obtaining in individual cases. However, the characteristics of motors are in most of the essential details especially adapted to rolling mill conditions. They permit of the centralization of the steam plant and the generation of power in high speed, highly efficient units. The authors have made the mistake frequently found in comparing estimates of the relative operating costs of steam versus other methods of drive. Why stop with the steam consumption, when one of the greatest savings results from the increased boiler efficiency due to the more uniform demand for steam made possible by the use of the fly-wheel motor-generator set equalizing the load in the electrically-driven mill. Tests would indicate that boiler efficiencies may be raised twenty per cent or more by relieving the boiler of these excessive demands for steam required by reversing engines.

My experience indicates that a comparison on the proper basis including all the items of first cost, chargeable against each method of drive, would show little if anything in general in favor of steam equipment in first cost, and will always show the electrically driven mill to be lower in operating costs. The speed and torque characteristics of the motors are ideal, there are no tendencies toward excessive speeds when the piece leaves the rolls and the motor is always in a position to exert its maximum effort when the maximum power is required.

The figures and curves of power consumed in rolling given by the authors, check within reasonable margin of the experience of the writer.

In considering the requirements of reversing rolling mill motors, it is interesting to note the similarity between the factors affecting their electrical design and those for a mine hoist. Both are required to accelerate rapidly, and to carry very heavy dead loads, during acceleration. In fact, in these respects the requirements of a mine hoist motor are frequently more severe than for the reversing mill motor. The roll motor is required to accelerate but little in addition to its own armature, and usually reversal and acceleration to partial speed are accomplished without any dead load, although the equipment should have sufficient capacity to accelerate rapidly with the piece in the rolls. On the other hand, the hoist motor must accelerate in addition to its armature the drums, ropes, cages and load which may be equivalent to several times the armature, and must always handle full load throughout the acceleration. It is true that the time allowed for accelerating a mine hoist motor is more than that allowed for the reversing mill motor, but the increased time is not proportional to the increased load to be accelerated, so that frequently from the standpoint of peak loads, the requirements for the mine hoist motor are more severe than those for the reversing mill motor.

The shocks to which a reversing mill motor is subjected are, of course, more severe, and very much more so than those to which a mine hoist motor is subjected, but are the same as those to which the ordinary non-reversing steel mill motor is called upon to meet, so that the reversing mill motor becomes essentially a direct-current motor capable of withstanding the peak loads met with in mine hoist service, constructed mechanically to withstand the shock and vibrations incident to rolling with the windings held firmly to prevent injury from the mechanical and electrical shocks.

The all important question is production, and in my experience the steam advocate has made a greater point of the speed of the steam mill as compared with the electric mill than he has on the questions of economy or first cost, although many have claimed these advantages also, and the present electrically driven mills are referred to by him as being slow due to the time required to accelerate. In this extremely important detail, the characteristics of the reversing rolling mill motor differ from those of the mine hoist motor apart from the effect of the time of reversal on the peak current taken by the motor. It is well known that time is required to build up and discharge a magnetic field: the rate being dependent upon the time-constant of the field winding.

The importance of this is suggested by the author, but apparently in the equipment thus far installed every reasonable means has not been resorted to, to bring about a rapid change of field and resulting rapid acceleration and retardation. The accumulative compound windings on the motors tend to increase the time of rolling by lowering the rate of acceleration and decreasing the time of retardation. This compounding is not necessary to protect the mill any more than it is necessary to protect non-reversing mills driven by direct-current or alternating-current motors, many of which are driven by motors without this provision or its equivalent. The compounding, of course, relieves the motor and generator from electrical shocks sufficiently to permit the use of slightly smaller equipment, but this saving is made at the expense of output from the mill. In the equipments we are now building for this work, we will not only take advantage of the shorter time required for accelerating and retarding the shunt motor to reduce to a minimum the time required for rolling, but are using in addition a special system of control, which will be described later in a paper. This takes advantage of the actual characteristics of the rise and fall of the magnetic field to produce a maximum rate of acceleration and retardation of the roll motor, thereby obtaining a faster operating reversing mill than any thus far built.

One of the most important details in the construction of a reversing mill equipment is the motor shaft, and in many instances this detail has been rather slighted. It is true that these shafts are protected by breaking spindles, but it must be borne in mind that the breaking of a spindle must in no way endanger the shaft. A moment's consideration will convince anyone that the motor shaft should be at least one-third larger in diameter to even protect it against injury from a strain sufficiently great to break the breaking spindle; even then there will be little or no factor of safety in the shaft, in spite of the difference in material used for shafting and spindles. In addition to this, the shaft is frequently subjected to extremely severe bending moments in the event of the breaking of a spindle on the diagonal. It has been our practise to recommend shafts much stronger than those installed, and I cannot but feel that eventually serious delays are bound to result from unnecessary weaknesses in this feature.

The question of motor voltages is too elementary to warrant discussion, although considerable importance seems to have been attached to it by the authors. Practically all of the reversing mill motors installed, including the first one, have been designed for voltages ranging from 550 to 750 volts, and where more than one motor has been used, they have been connected in series, resulting in a voltage of the combination from 1000 to 1500 volts. Here as in most problems, involving larger powers, it is essential to use as high voltage as is consistent with reliable operation and reasonable first cost, and the writer feels safe in predicting higher voltages for this work when more experience has been gained with high-voltage direct-current units of large capacity.

The question of windings, compensated and commutating, is also ancient history, the equipments for this service always having been provided with these special means for improving commutation.

E. S. Jefferies: The question brought out in Sykes' and Hall's paper regarding engine builders' claims is very interesting, and

I would like to point out a few results obtained on the Steel Company of Canada's mill referred to in their paper.

This mill has been operating since the early part of 1913 with very good results, and the experience gained brings out some very interesting answers to the five general questions raised by the steam men in favor of steam rather than electric drive. In the tables herewith, are complete costs covering this installation, and operating costs for the three years 1913 to 1915, and an average for the same period.

As the Hamilton Mill purchases power, I cannot give any comment on the relative costs of steam and electrical drive. However, in Table I is given a comparison showing the operating costs, interest on investment, depreciation and miscellaneous charges covering this particular installation. This shows an average total cost for the three years of only 43.1 cents per ton. This figure includes a depreciation charge which considers the installation as valueless at the end of a 20-year period, and a miscellaneous charge which includes all power for lighting, tables, crane, conveyor, pumps, motors, etc., used in this mill. The largest item, power cost, is exact, as it is metered, and the other items are charges made direct with no estimating, the result being that the total is an exact cost without any estimation whatever, in arriving at the results. These are the actual book figures.

TABLE No. 1.

Year	1913	1914	1915	Average or total	Per cent
Operating	9 months	8 months	12 mo.		
Tonnage,	119,230	92,622	174,460	386,312	
Kw-hr. per ton,	23.9	22.8	21.5	23.4	
Power cost,	$.0160	$0.153	$.0144	$0.157	36.40
Repairs and maintenance	0.077	0.009	0.004	0.006	1.40
Miscellaneous supplies	0.004	0.005	0.003	0.004	0.90
Labor in operation	0.014	0.016	0.013	0.014	3.25
Total operating cost	0.185	0.183	0.164	0.181	
Interest on investment ($156,000)	0.078	0.101	0.054	0.73	16.90
Depreciation (20 years)	0,065	0.084	0.045	0.060	13.95
Total operating and fixed costs	0.328	0.368	0.263	0.314	
Miscellaneous	0.126	0.133	0.115	0.117	27.20
Total cost	0.454	0.501	0.378	0.431	100.00

The question of energy saved during reversal is a very interesting subject in connection with a paper of this kind. How many rollers on reversing mills in this country are paid straight time? How many are paid tonnage rates? The answer is that practically every mill is paying tonnage rates, with the result that speed is the sole question in the operators' mind. Furthermore this speed is obtained by using live steam to reverse the engine rapidly. In a motor-driven mill a certain per cent of the stored energy in the rotating parts is saved by regeneration, and is stored in the flywheel for future use, regardless of operating conditions. The one great advantage in answer to question 4 of low power consumption with partial load is that the motor-generator set can be disconnected from the line when the mill is idle, thereby entailing no stand-by losses, such as are met with in steam installation.

The time taken for the Hamilton motor to reverse is still ahead of the handling of the metal on the tables, manipulation, screw-down, etc. That is, the motor is waiting on the mill. Since the figures given by Sykes and Hall on this mill were taken, we have developed a new governing relay which has given us considerably more positive protection and allowed more speed and, therefore, capacity. We have obtained a speed of 125 rev. per min. on our long passes which when rolling from sixteen to seventeen elongations, saves considerable time.

The advantage of an electric mill may be summed up as follows:

1. Low cost of power.
2. Low cost for repairs and maintenance.
3. Small time to get under way from complete shut-down to rolling conditions.
4. Speed proportional to displacement of controller lever from off position.
5. Part of rotative energy of mill parts recoverable for useful work.
6. Stand-by losses nil.
7. Simplicity of control.
8. Few delays necessary.
9. Motor does not race when steel leaves rolls.
10. Constant turning moment.
11. Ideal load to add to any generating station.
12. Lends itself to centralization of power.
13. Simplified mill lay-out.
14. Mill breakages less.
15. Small area or ground space needed.

The floor space necessary for the equipment described was 40 feet by 125 feet, which allows ample room between machines and wall and switchboard, no apparatus being cramped in any way. A 40-inch mill could easily be installed in this same area. In case of necessity the flywheel set need not be located in close proximity to the mill motor, so that in adapting a mill under extreme conditions where very little floor space was available, the flywheel set could easily be located some distance away where more area could be obtained. The real estate charges on some mills located in thickly settled communities must be considered, and in comparing this area with the area necessary for boilers, coal handling machinery, steam engines, pumps, etc. the result is good.

After the mill has been down for any reason, the time necessary for the attendants to have the entire equipment ready for maximum rolling conditions is less than ten minutes. It is doubtful whether a steam boiler equipment could be gotten under way from absolute standstill to running conditions in less than four hours. The simplicity of the control as compared to the levers, links and auxiliary cylinders necessary for the steam engine is very noticeable. The entire control wiring between pulpit and power house is contained in a one-inch conduit. All parts of the control are entirely accessible, and any part needing repairs can be changed in a very few minutes. Repairs have been exceptionally low, the largest item being the brush renewal. Delays in the last three years due to this equipment exclusive of the development period, have not amounted to twenty-four hours, and this period was taken up at various times more to be doubly sure that the equipment was in good order rather than take any chance.

When the mill is idle, the flywheel set can be disconnected from the line and allowed to rotate, which means that there is absolutely no loss as compared to steam equipment having to keep the boilers under steam, the steam-line condensation, small leaks, etc. When the steel leaves the roll, there is no racing, as would be the case in the steam engine run by the average operator, the motor maintaining uniform speed, corresponding to the displacement of the control lever from off position. Such complete control of the speed of the mill is ideal when steel is entering and leaving the rolls, as there is no change of speed unless the operator so wishes. The motor exerts a constant turning moment in all positions, whereas the steam engine has its maximums and zeros, every revolution. The saving due to the return of the rotative energy of the mill parts to the flywheel gives a means of saving power which is normally lost in steam-driven mills. If 60 per cent of the rotative energy of the mill motor is returned to the flywheel, 60 per cent of this, namely, 36 per cent of the whole, is available again on the mill shaft for active work.

To any plant, whether purchasing power from central station or receiving power from their own power house, the Ilgner system adds an ideal load due to the fact that it is a fairly constant load. If the mill is run to capacity, the power variations will be very slight. The central station load applies in the same way and lends itself, where power is being purchased on a peak basis, to a very low rate. For a large power plant, the increased load does not amount to very much. Taking as an example of this the Hamilton mill: A 1200-kw. generator capacity would easily take care of the load. Where mills are located at various points in the plant, which, from a steam power point of view is inefficient, the Ilnger system eliminates such inefficiency by centralization.

The exceptionally low cost of power is probably the most striking feature of this system, the figures shown being actual figures in no way having been adjusted for cost-keeping purposes. The simplicity of the mill lay-out is another feature which must be considered.

D. M. Petty: I have in mind one or two points I think it would be well to consider in comparing electrical and steam reversing mills. One of the most important points is the flexibility of lay-out. Steam engines, in order to reduce condensation losses, must be near the boiler plant, and while it is possible to locate reversing drives at any position that may be necessary, the fact that mills in recent years are being much more frequently laid out with the idea of reducing the distance that the steel has actually to travel from the soaking pit to the finished product, whatever that may be, is of considerable importance.

The commutators of reversing mill motors I think are probably the most important of electrical problems, because with the reversing mill d-c. drive the commutator is naturally the place where most trouble will be experienced, and most trouble has been experienced. This trouble is not only electrical but mechanical in a good many respects. The number of brushes on the commutator is a direct item in the maintenance charges, but the size of the commutator has a great deal to do with the mechanical troubles which may arise.

So far as the speeds of the motor itself are concerned, they are governed very largely by the speed at which it is desired to run the mill, but the speed of the generators attached to the motor-generator set is not so limited, and I think it is pretty safe to say in regard to d-c. steel-mill motors and generators that the lower the speed, within reasonable limits, the more satisfactory the operation and the lower the operating charges.

The speed of reversal has been emphasized. This should be taken into consideration, but I feel sure that electrical engineers will have no trouble meeting the requirements. It is far more important to insure reliability of operation than to obtain rapid reversal. Size of bearings, method of lubrication, size of shaft and holding of field coils and armature coils in place against heavy shocks are points that stand near the head of the list in importance, in order to make a mill drive reliable.

R. Tschentscher: I would like to correct, first, the statement made by Mr. Hall that the first reversing set was put in at Gary. The first reversing set was in operation, in December, 1905, at Chicago. It was a very small set, about 75 h.p., and the next set of a much larger size, was put in at the same place.

I think there is too much stress being laid on the question of the electrical characteristics of these equipments. As the result of my observation and my experience in the last ten years in operating one of these sets, it is my opinion that the designers should lay more emphasis on the physical arrangement, than on the time of reversal; for example, on the stiffness of the shaft, to prevent oscillations, etc., and on the size of the bearings, to put off as far as possible the time when the bearings must be renewed.

When the first set was purchased in this country, the time of reversal was a subject which was given very careful consideration.

I think that the time of reversal was specified as three seconds. As a matter of fact, there are practically no mills,—there might be one or two small mills—that can use a reversal of three seconds, that is from full speed in one direction to full speed in the other.

Much has been made out of the rapidity of reversal of the steam engine—true, it does reverse very rapidly, but any one who has watched a blooming mill operate will be impressed with the fact that the reversal is fast, but the time consumed from the moment the steel enters the rolls and the rolls grip the piece, and the engine is started up again, is from one to five seconds, and it is a fallacy to put too much stress on the question of the time of reversal when such rapid reversals cannot be used. The piece has to be manipulated, the screw-down operated, etc. The time required for such operations determines the time required for motor reversal.

Any one about to purchase an outfit always has the question of the relative merits of the reversing drive versus the continuous rotation mill, to decide. Efficiencies that may be guaranteed at full load, to me are more or less valueless. What may be called the capacity factor, the average yearly input to the capacity of the outfit, is very low, indeed. I think in continuous rotation mills it will be found that this capacity factor will vary from 15 to 40 per cent and in the reversing mills from 30 to 70 per cent. Figures I have taken show, in a reversing mill operating for twenty-four hours on the basis of the input to the motor of the motor-generator set, divided by the full kw. rating of that motor, that 60 per cent is extremely rare. On that basis, it appears to me that we ought not to spend too much time in attempting to get the last bit of efficiency, but rather get reliability physically, so that when the demands for the mill are increased in times of high pressure and high prices, the outfit will then respond.

H. D. James: I think that we all appreciate that the development of the electrically driven reversing mill is another opportunity to "do it electrically." We all of us believe in electric power, many of us believe in central station power. The use of the electric rolling mill has enabled us to occupy another field with our motor applications.

We have learned a great deal in the past ten years about this reversing drive, and I want to emphasize Mr. Tschentscher's remarks that the time of reversal is not the main essential. It was my privilege to assist in developing the drive of which Mr. Tschentscher spoke, and I wish to add that, he himself, did a great deal to make that drive a success. We started out with the idea that time was one of the most important points, and we ended with other ideas. The tendency now seems to be towards a little more time, and a little more substantial mechanical construction.

F. G. Liljenroth: Having been very closely connected with the European practise of reversing rolling mills during the past ten years, it is with the greatest interest that I have read the above paper. As Messrs. Sykes and Hall point out, there is quite a difference between the practise in Europe and in the United States, the most noticeable differences being as follows:

REVERSIBLE MOTOR

It seems to be the general practise in the United States to divide the motor, especially the larger sizes, into two units on the same shaft, while the European practise, at least as far as the leading electrical manufacturing companies are concerned, is to build the motor as a single unit, even for the very largest capacities. So, for example, there are to be found in Europe several reversible motors of the same size, that is, with the same torque as the Bethlehem steel motors, which are built in single units, and as far as I know, there is at least one single-unit motor built which has a maximum torque of 240 meter-tons—1,750,000 ft-lb.

The advantages of using single-unit motors are evident: lower first cost and better efficiency, besides the advantages of having to deal with only one commutator, which part is always the weakest in a direct-current machine. Such a single commutator need not be larger than each of the commutators of a two-unit motor, inasmuch as the voltage which is used is as high as from 1000 to 1500 volts and consequently the current is the same as at 2 × 600 volts. There seems to be no disadvantage in using a single-unit motor instead of two. It is true that on account of the higher operating voltage the potential between the brush edges (or rather the voltage which would appear between the brush edges on account of the armature reaction, if this was not compensated for by the commutating poles) is higher than if the machine were divided into two parts, but by correctly determining the ratio of the tangential width of the brush to the commutator pitch, etc., it is possible to limit said potential at maximum peak load to less than 2½ per cent of the operating potential, that is, at 1200 volts to less than 30 volts which is allowed even according to American practise, as stated by Mr. Lamme in his very excellent A. I. E. E. paper dealing with the Commutation of Direct-Current Machines. There are, of course, just as here in the United States other provisions made in order to completely compensate for the potential between the brush edges under all conditions of load. For example, these motors are always equipped with compensating winding, as well as commutating poles, the winding of the latter being placed as close as possible to the armature in order to reduce the leakage field of the commutating pole to the lowest possible value. Furthermore, the commutating poles are tapered and have the same axial length as the armature. In order to avoid a time lag at rapid load fluctuations between the armature current and the commutating field, it has been found advisable to make the commutating poles of laminated iron. The air gap of these poles is made very large, at least one inch, while that of the main poles is usually about 3/16 in. The armature winding is furthermore provided with numerous equalizing connections, at least one for each slot.

With the above design it has been found that the motors will operate absolutely sparkless, even for the highest peak loads and in watching the commutators of several such machines, they have operated so perfectly that it was impossible to determine whether they carried a load or not. This applied even to peak loads where the non-compensated potential between the brush edges would have been approximately 40 volts. The average voltage between the two commutator bars, that is, the operating voltage divided by the number of commutator bars between two brush positions does not, for such machines, exceed 20 volts which must be considered a conservative value.

GENERATORS

It is the general European practise to use two generators of from 500 to 750 volts (usually 600 volts) connected in series and consequently the same practise as in the United States. For the newest installations the speed is, however, considerably higher than was the case some years ago, and which still seems to be maintained in the United States. But this, only refers to the modern installations which were completed shortly before and after the beginning of the war. Sufficient time has elapsed since these motor-generator sets were installed and the results obtained have clearly demonstrated that such speeds are entirely satisfactory and safe, and, as far as Europe is concerned, they have caused a revolution in the design of such machines. The first cost is considerably lower, while the space required is also much lower and the efficiency higher. Comparing such a flywheel motor-generator set with the older designs, one is immediately astonished by its small dimensions. The Bethlehem Steel set could have had a speed of at least 514 instead of 375 revolutions, that is, at 60 cycles the induction motor should have had 14 poles.

With the higher speed the motor generator can be built much smaller and this particularly refers to the flywheel. For a certain WR^2 it is evident that the mass of the wheel and consequently also its weight can be the same, independent of what speed is chosen, if only the peripheral speed is maintained constant. In most cases, however, the diameter of the flywheel is limited by shipping facilities to about 4 meters—13 ft. and the peripheral speed by the permissible stresses at maximum runaway speed, this usually being taken as 25 per cent above normal speed. The stresses should in no part in the wheel at its runaway speed be permitted to exceed 10kg. per sq. mm. or about 14,000 lb. per sq. in. which values at normal speed would correspond to about 9000 lb. These values are, as seen, very low and conservative, and it is not necessary to use any especially expensive material in the wheel, but only ordinary cast steel with an elasticity of 40,000 and an ultimate strength of approximately 70,000. Regardless of these low stresses, it is possible, by using a suitable design of flywheel, to go to a peripheral speed of as high as 430 feet per second and still not exceed a stress of 14,000 lb. per sq. in. at runaway speed. From the above it follows that the lowest speed which should ever be used for such a flywheel should be:

$$\frac{430 \times 0.8 \times 60}{13 \times \pi} = 500 \text{ rev. per. min.}$$

The largest generator which can be built at this speed has a maximum load, that is, peak load, of about 4300 kw., this being under the assumption that the peripheral speed of the armature is not to exceed 150 feet per second and the average voltage between the two commutator bars not to exceed 20 volts and that at peak load, amperes × armature conductors per cm. circumference is about 800.

The Bethlehem motor requires approximately 8500 kw. and it follows, therefore, that its motor generator could readily have been built for 500 revolutions with two series connected generators each for 600 volts. The weight of the flywheel could have been reduced in proportion $\left(\frac{375}{500}\right)^2$ or to approximately one-half and the flywheel effect would still have been retained. This is under assumption, that the diameter of the Bethlehem flywheel is about 13 feet. It is possible, however, that there are other reasons for using the low speed and it would be interesting to obtain information in regard to:

1. The largest permissible diameter of the flywheel limited by transportation facilities.
2. The percentage of runaway speeds which are usually specified.
3. The corresponding permissible stresses in the flywheel as well as the properties and the material which is used.
4. The corresponding peripheral speed whose relation to the stresses is dependent on the design of the flywheel.

EXCITATION

As far as the excitation is concerned, the European practise comprises what is known as the "indirect" regulation, that is, the rheostats or controllers are not inserted in the generator or motor fields, but in the fields of the exciters. The exciters are used, one for the generators and one for the motor, the voltage of the exciters being regulated. The exciters are, therefore, in turn magnetized from a third exciter which consequently can be very small, working normally as a shunt generator with constant potential. These three machines are driven by a common small induction motor.

The advantages of this scheme are: smaller equipment, lower first cost and especially greater reliability as far as the rheostats and controllers are concerned, in that the currents which have to be handled are only from one to two per cent of what would be the case if the “direct” excitation were used. For rolling mill service it is evident that the control equipments have to withstand very severe service both electrically as well as mechanically on account of the rapid breaking of comparatively large magnetic energies and also due to the fact that they are in almost continuous service. The advantages of smaller equipments which are obtained by the smaller apparatus used with indirect excitation are, therefore, obvious. The excitation will be just as rapid as by the direct method, on account of the fact that the magnetic energy stored in the small exciter fields is negligible compared to the large machines.

The compounding is usually made in the way that the main poles of the generators have an opposing series winding which therefore does not have to be reversed. Against this practise it may be argued that an assisting compound winding on the motor would be better, inasmuch as the torque will be increased by strengthening the field. This, however, is more or less an imaginary advantage, as for machines of this kind the saturation curve at normal speed is so flat that a large increase in the field current creates a very small or almost no strengthening of the field.

Concerning the safety devices and the arrangement of the automatic load regulation, etc., the European practise involves several quite interesting departures from the practise in the United States, but space does not permit of further discussion of this subject.

Brent Wiley: It would be well to consider the blooming mill equipment from the standpoint of the entire mill drive, as practically every steel plant is composed of finishing or semi-finishing mills, as well as blooming mills.

During the last eleven years more than three hundred large motor units, totalling over 500,000 h.p., have been installed to drive the main rolls of steel mills.

The following list gives the electrically driven reversing blooming mills installed, and on order in the United States and Canada. The majority of the equipments have been purchased during the last few years.

				Installed
—	Blooming	Mill	—Algoma Steel Co. Sault Ste. Marie, Can.	1911
34 in.	“	“	—Steel Co. of Canada, Hamilton, Ont.	1913
34 in.	“	“	—Central Steel Co., Massillon, Ohio,	1914
35 in.	“	“	—Bethlehem Steel Co. Bethlehem, Pa.,	1915
35 in.	“	“	—United Steel Co., Canton, Ohio,	On order.
40 in.	“	“	—Inland Steel Co., Indiana Harbor,	“ “
32 in.	“	“	—Inland Steel Co., Indiana Harbor,	“ “
40 in.	“	“	—Illinios Steel Co., Gary, Ind.	“ “
40 in.	“	“	—National Tube Co., Lorain, Ohio	“ “
34 in.	“	“	—Chattanooga Steel Co., Chattanooga	“ “
35 in.	“	“	—Mark Mfg. Co., Indiana Harbor,	“ “
34 in.	“	“	—Ashland I. & M. Co., Ashland, Ky.	“ “
34 in.	“	“	—Keystone Steel & Wire, Peoria, Ill.	“ “

REVERSING MOTOR EQUIPMENTS—FOR OTHER TYPES OF MILLS.

	Installed
30 in. Universal Plate Mill Ill. Steel Co., S. Chicago,	1908
" Plate Mill —Am. Sheet & T.P. Co., Gary, Ind.	1910
" " — ditto	1910
28 in. Structural Mill—Inland Steel Co., Indiana Harbor,	On Order
27 in. Universal Plate Mill Mark Mfg. Co., Indiana Harbor	" "

The principal object of the earlier installations was to utilize cheap power and the incidental advantages possible were not taken into account. Experience has demonstrated that motor drive has many favorable features which are of economic value in not only the every day operation of the mill, but assist most materially in the development of the method of operation.

Motor drive gives the greatest latitude regarding the arrangement and design of mill and of the entire plant. Motors can be designed with either high, intermediate or low speed, and with a wide variation in maximum or pull-out torque. Adjustable speed motors give a wide range of operating speeds, with very economical operation of mill, either for constant torque or constant horse-power requirements. The regulation of the alternating-current motor is very close, even under a wide range of load, varying only about two and one-half per cent from light to full load. It is capable of standing heavy overloads frequently for comparatively long periods, without undue strain or deterioration. The ease with which power readings can be made instantaneously and for any desired period is of great value in compiling records to ascertain the effect and value of any change that is inaugurated in the development of the mill design.

The general experience in the operation of a new mill is that the results obtained, after a few years, are radically different from the ideas of the possibilities and expectations of what could be accomplished when the design was first conceived. In the majority of cases it is necessary to make a number of assumptions regarding the possibilities of each particular portion of the mill, including capacity of heating furnaces required, permissible reductions per pass, speed of rolling, size and shape of product most desirable from the standpoint of trade demands. The mill is developed as more information is obtained regarding these factors, and the incidental advantages of motor drive have played an important part in accomplishing the most satisfactory results in reversing blooming mills, as well as other types of rolling mills, as the general advantages are the same for all types of motor equipment.

First Cost

It is assumed that the plant is designed with motor drive for the blooming mill, finishing mills, and for the auxiliaries.

The average load on the electric power station to drive a reversing blooming mill with maximum peaks of 15,000 to 20,000 h.p. is approximately 3000 to 3500 h.p., with variations of not more than 15 per cent during the active rolling period of the mill. The station capacity will be divided approximately 80 per cent for motors of auxiliary machines and finishing mills and 20 per cen tfor the reversing mill equipment. In other words, it will require a comparatively small increase of power plant to provide for the blooming mill work which is quite a contrast with the requirements in an addition to a boiler plant for a steam engine-operated blooming mill.

Furthermore, the addition of a very uniform load assists in equalizing the total plant load, and thereby increases the efficiency of operation.

The use of central station power is also a very material factor in reducing the first cost, and many steel plants are taking advantage of this point as well as of other favorable factors which purchased power affords. At present, there are more than fifty steel plants obtaining part or all of their electric power from central stations, and are using a total of approximatley 425,000,000 kw-hr. per year, which is approximately 18 per cent of the total electric power required per year by the iron and steel industry.

ECONOMY OF OPERATION

There is more economy of operation to be gained by the electrification of the reversing blooming mill than of any other type of mill. In the case of the averaging existing steam engine-driven mill, the steam consumption can be reduced fully fifty per cent by use of motor drive. This comparison is made on the basis of using electric power as furnished by steam turbines at approximately 5000-kw. capacity. Undoubtedly there are many cases where the gain would be even greater than this, but on account of the limited test data available regarding the steam requirements and general analysis of plant conditions, it has been difficult to establish these facts definitely.

H. S. Page: Analysis of the sequence of operations during rolling might serve to bring about closer unanimity of opinion in regard to the permissible time of reversal. The actual reversal occurs during the time the metal is out of the rolls between passes; is from a comparatively low speed in one direction to about the same, or lower speed in the opposite direction, and can easily be accomplished while the metal is being returned to the rolls. After the metal enters the rolls it is of the utmost importance to have a driving motor capable of accelerating the mill to the maximum speed of the pass just as quickly as possible. The retarding action of any device installed for the protection of the motor should be carefully considered; as the function of most of these auxiliary devices is to prevent rapid acceleration and thus limit the output of the mill.

A few comments might be added on the subject of general design of reversing mill apparatus which is treated at some length in the paper. Generally speaking it is permissible to sacrifice efficiency to a slight degree in order to gain more rapid acceleration and for this reason it seems advisable to work all magnetic and current carrying material in the motor armature at the highest possible densities in order to reduce the stored energy to a minimum, the voltage being determined by the most economical arrangement of armature conductors and commutator segments. A decided advantage is gained by designing the motor with a view to cooling by means of forced ventilation. Valuable protection of commutators and brushes from the sharp steel mill dust and grit, as well as insurance from burnouts caused by deposits of this same material can be obtained by blowing sufficient thoroughly washed air through the motor for the complete ventilation of the dynamo room. As mentioned, before, it would seem advisable to let the voltage of these equipments be fixed by conditions governing the design of the motor rather than choose a voltage best suited to the generating set. The speed-voltage curves submitted with the paper apply fairly well to present day design but as the tendency is toward higher speed generating apparatus, it is questionable whether they will apply a few years hence.

The rapid fluctuating speed and load conditions required by the cycle of operation of this type of equipment makes the question of rating, especially of the driving motor a rather vexed one. A very convenient working basis for heating can be taken as the maximum continuous safe load capacity at full field on the motor and maximum continuous generator voltage. If some such rating is established and the heating properly calculated from the rolling cycle for each installation much of the trouble which has been met in the past with electrically driven rolling mills will be avoided. Of course in addition to this it is necessary to make proper allowances for the range in load and speed as well as to carefully consider the mechanical stresses which are brought about by the rapidly fluctuating load conditions.

Peter Lindemann: There is one point in my mind which the schematic diagram shown in Fig. 3 of the paper does not make entirely clear.

It may be that there are other controlling devices used which are not shown in this diagram, and which will prevent the starting of the direct-current motors while the generator field rheostat is in neutral position, for it seems to me that the shifting of the brush holders on one of the direct-current separately excited generators would cause voltage to be built up on the closed motor circuit.

It would be interesting to know what precaution, if any, has been provided against such an occurrence.

Alex. Gray: One of the previous speakers brought up the question of the speed of the flywheel motor-generator set, and stated that whereas we use a speed of 375 rev. per min., European engineers have gone up to 500 rev. per min. for the same horsepower output. To me this would indicate one thing only, namely, that Eurpoean engineers work much closer to the limit than we care to do on this side.

I once made the remark that there were limitations in the design of electrical machinery, and was told by a well known operating engineer that such limitations did not exist, and that as soon as the operating engineer demanded anything, the designing engineer found a way to overcome his limits and supplied the demand.

Mr. Hall in his paper has drawn attention to the fact that for each speed there is an output rating that cannot be exceeded unless the engineer is looking for trouble. This may be explained as follows: Taking a machine of given diameter, there is a safe maximum speed at which this machine may be run, and the output is then limited only by the length of the armature core. As this length is increased, the voltage generated in each turn of the armature also increases until, when a value of about 6 volts between adjacent segments is reached, interpoles become necessary. With inter-poles supplied, the machine may be further lengthened until, when a value of about fifteen volts is reached between segments, the machine becomes sensitive to changes in load and is liable to flash over. Compensating windings must then be supplied, if the output is to be further increased.

Evidently, then, the 500-rev. per min. European machine is run either with a greater peripheral velocity, or with a greater value of voltage between segments than in the case of the 375-rev. per min. American machine. From the fact that they are designed closer to the limit, much more care is necessary in the construction of the apparatus, so that the machine is not necessarily cheaper.

In regard to the rating of the motors, it must be clearly understood that while the motors in question have a rating of 10,000 h.p., at 100 rev. per min., they would become hot with a continuous output of about 4000 h.p. On the other hand, if the machines were large enough to dissipate the loss corresponding to a 10,000-h.p. load, they would have become so long as to operate badly with regard to commutation.

It is, therefore, rather hard to decide how they should be rated, because they are designed as 10,000-h.p. machines so far as commutation is concerned, and as 4000-h.p. machines so far as heating is concerned. Since the former is the more important limitation of the two, it seems reasonable to give them a rating of 10,000 h.p. maximum.

With regard further to the rapidity of reversal of the generator voltage, it is of interest to note that, since the machines have compensating windings, the air-gaps can be small, and the shunt excitation be almost negligible. It is, therefore, quite within reason to put a non-inductive resistance in series with the field-coil circuit so as to reduce the time constant of this circuit and thereby allow the field to build up rapidly; and this would not reduce the efficiency of the machine to any appreciable extent, and, moreover, would allow the rate at which the machine builds up to be adjusted. It would seem from the discussion, however, that the machine reverses as rapidly as the mill engineer desires.

Wilfred Sykes: The discussion by Mr. Pauly indicates lack of experience with this type of apparatus. The question of rating has been given considerable thought by engineers designing reversing mill equipments, both here and abroad, and it has been the practise to rate reversing mills on the maximum operating peak loads as it is these loads that fix the size of the apparatus, and not the continuous capacity based on heating. These loads do not represent the absolute maximum capacity of the machines without injury, but are the peaks that are ordinarily carried during the operation of the mill.

Mr. Pauly's remarks regarding the similarity of the reversing rolling mill and the mine hoist motors are correct as far as the general system used is concerned, but the operating characteristics of the reversing rolling mill motor, and the control problems are entirely different, and much more difficult than those of the mine hoist. The shocks which the reversing mill motor is subjected to are very much more severe than those of the non-reversing mill motor where the conditions are comparable, such as, for instance, the three-high blooming mill compared with the two-high blooming mill. In such cases the continuously running motor has a flywheel between it and the mill, and the shocks on the parts of the machine are very much less than with the reversing motor where the flywheel effect is reduced to a minimum.

Mr. Pauly's remarks about the speed of operation are answered very well by the discussion of Mr. Tschentscher. The same opinion was held ten years ago regarding the necessity for high rate of speed change, but after practical experience obtained with electrically driven mills it was obvious that extreme steps were not necessary to obtain high rate of reversal, and when Mr. Pauly has gained some actual experience with these mills, no doubt, his views will change.

The question of size of motor shaft, and upon which Mr. Pauly places so much stress, seems to be catering rather to the old idea of making a part massive without the appreciation of the conditions under which it operates. It is obviously useless to make the shaft many times stronger than some other part of the machine which is just as liable to be broken, and in designing equipments it has been our object to obtain the accumulated experience of motor and engine builders for this type of mill. A shaft diameter out of all proportion to the output of the equipment, or the size of the mill may be an excellent talking point in selling apparatus to an ignorant customer, but is not good engineering.

Regarding the discussion of Mr. Petty. It is not feasible to reduce the speed of the generator below certain limits, due to the fact that the flywheel diameter is limited by transportation facilities, and the flywheel effect necessary might mean prohibitive weights with speeds too low for economical design.

Mr. Lilgenroth brings up a number of points regarding the design of European compared with American reversing mills. The question of using one instead of two motors for the large equipments has received a great deal of consideration, and it was with a full knowledge of the European practise that the equipments now being built were designed with double motors. The question of safety to attendants is one on which a great deal of stress has been placed by mill operators, and there was a very great objection to the use of voltage higher than 600 across an individual machine. In the United States we must also face less skillful attendants, and the use of a 600-volt machine with 1200-volt insulation, such as the Bethlehem machine is, gives us a greater factor of safety than would be possible if we used single motors with, say, 1500 volts on the windings. The design features brought out, having been found desirable in Europe, are all incorporated in the machines which have been built.

The question of generator speed is one that has been given a good deal of thought, and it might be of interest to mention that the 500-revolution generators running at the Steel Company of Canada's plant repeatedly carry loads of 5000 kw. each, and it is quite possible to build generators for 500 revolutions to supply power to the motors at Bethlehem. On the other hand, using a speed of 375 r. p. m., there is greater leeway, and a greater margin could be obtained to cover the uncertainty of operation which was a factor on the Bethlehem installation. This mill was installed for rolling a very wide range of products, and different classes of steels, and it was practically impossible to predict before hand just how much power would be required. For this reason a conservative design was adopted, the wisdom of which has been shown by the operating conditions of the mill, since installed.

Regarding the question of flywheels, we have found it desirable to limit the operating peripheral speed to approximately 300 ft. per sec., although the stresses at this speed are very low. This is due to the uncertainties as to the quality of metal obtained in castings. The conditions in the United States are very different from those in Europe where cast steel wheels, for higher speeds, can be readily obtained.

Regarding the question raised by Mr. Lindemann, provision is made in the controller for the generator fields to prevent the motors being started in the way he mentions.

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MOTOR EQUIPMENTS FOR THE RECOVERY OF PETROLEUM

BY W. G. TAYLOR

Abstract of Paper

The work of drilling, pumping and cleaning oil wells is very successfully handled by slip-ring induction motors. With the cable-tool method of drilling a special arrangement of controllers and resistance is used to obtain the required fine speed control. Similar motors are used for both this and the hydraulic rotary method.

Pumping and cleaning, which includes 'pulling' the rods and tubing, are in most cases all performed by the same motor which may be a 'Y-Delta' or a two-speed machine, depending upon operating conditions. Both of these motors are double-rated, the low rating being used for pumping and the other for pulling and cleaning. High efficiency is essential on the pumping duty and high torque for the heavy work of pulling and cleaning the well. For both types of motors special control features are used to properly protect the equipment as well as to make it most convenient for the operator. For wells pumped by jack-rigs, a portable hoist is employed to pull rods and tubing.

This paper presents data covering the horse power requirements and kilowatt-hour consumption for the various operations in drilling and maintaining producing oil wells.

THE GRADUAL decline in production which is characteristic of all oil fields as well as the great losses sustained with the usual methods of steam operation are the factors which generally furnish an incentive to the producing company to electrify its wells. The economy thus gained often gives the wells a longer lease of life, as it enables them to be pumped at a profit at a lower daily production than would otherwise be possible. In most cases economy is only one of the several advantages of motor drive which are taken into consideration, these including greater reliability, simpler and more accurate speed control, steadier speed, greater safety and lower insurance rates than with other types of motive power. These advantages on any motor application are too well known to warrant more than incidental mention.

The choice between alternating and direct current is generally determined by the available power supply and for this reason induction motors are used on nearly all electrically operated wells. Several isolated generating plants are in operation which were installed for the purpose of carrying an oil well motor load and which were designed for alternating current because of the inherent superiority for this service of an induction motor over a direct-current machine. Although the latter may at first appear to be a more advantageous type of motor on account of the speed variation obtainable by field control without material reduction in efficiency, yet when it is taken into consideration that oil well motors must often carry sudden and severe overloads and be frequently reversed at full speed, and are subjected to much abusive handling by unskilled operators, the overload limitations of a direct-current motor prove to be a severe handicap. A more complex control is necessary to protect the motor, and if this is not provided the depreciation of the commutator is rapid on the heavy duty.

There is a large number of varied operations which oil well motors are called upon to perform, and these fall naturally into three groups; drilling, pumping and cleaning. The process of drilling a well includes the operations of handling the drilling tools and the casing with which the hole is lined, and of removing the drillings by bailing or hydraulic flushing. The work of pumping includes such operations as are occasionally necessary to free the pump and valves from sand. The cleaning of a well is a process which varies with the conditions encountered. It is always necessary, however, to pull out the rods and tubing, which is known as 'pulling' the well. The accumulated sand and sediment are then removed by bailing or hydraulic washing, and may first require loosening up with a light 'string' of drilling tools. Swabbing is sometimes done to improve the flow of oil.

The most logical method of applying motors to these operations is to use a different machine for each of the three groups, as this not only involves the least complication in design, but also requires the minimum investment by the oil company, consistent with efficient operation. It has, however, been found more practical in most cases to use one motor for the drilling process and another for all the work involved in pumping, pulling and cleaning the wells.

DRILLING

The two methods of drilling which are in general use in the United States are the standard or cable-tool method, and the hydraulic rotary method. The former employs a walking-beam from the end of which a heavy stem and bit are suspended by a steel wire or manila rope. These churn the hole by the up-and-down motion imparted by the beam, the strata thus being penetrated by percussion. The drillings are mixed with water in the hole and are removed at intervals by a 'sand-pump' or bailer. As the hole deepens, iron or steel casing is inserted in approxi-

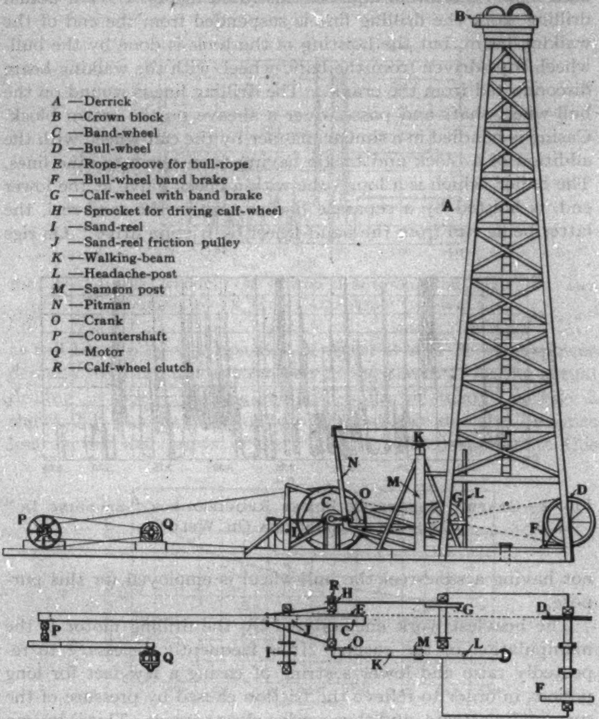
B
A —Derrick
B —Crown block
C —Band-wheel
D —Bull-wheel
E —Rope-groove for bull-rope
F —Bull-wheel band brake
G —Calf-wheel with band brake
H —Sprocket for driving calf-wheel
I —Sand-reel
J —Sand-reel friction pulley
K —Walking-beam
L —Headache-post
M —Samson post
N —Pitman
O —Crank
P —Countershaft
Q —Motor
R —Calf-wheel clutch
A
K
N
M
O
C
G
L
D
P
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FIG. 1—ELEVATION AND PLAN OF MOTOR-DRIVEN STANDARD CALIFORNIA OIL WELL RIG

mately 20-foot lengths, screwed together, but may not be used where there is no danger of caving.

The arrangement of the standard motor-operated drilling rig used in the California fields is illustrated in Fig. 1. For actual drilling work the drilling line is suspended from the end of the walking-beam, but the hoisting of the tools is done by the bull-wheel, rope-driven from the band-wheel, with the walking-beam disconnected from the crank. The drilling line is wound on the bull-wheel shaft and passes over a sheave on the crown block. Casing is handled in a similar manner by the calf-wheel, with the addition of a block and tackle having from seven to nine lines. The bailer, which is a long tube with a check valve at the lower end, is hoisted by a separate line wound on the sand-reel, the latter being run from the band-wheel by friction drive. On rigs not having a sand-reel the bull-wheel is employed for this purpose.

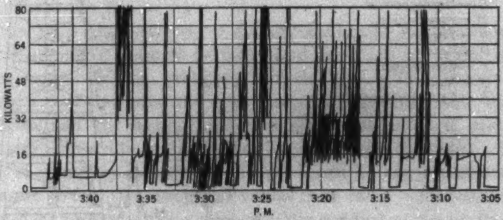


FIG. 2—GRAPHIC RECORD OF POWER REQUIRED FOR "SPUDDING IN" CASING IN A CALIFORNIA OIL WELL

The heaviest work encountered by the drilling motor is the manipulation of the casing. It is frequently necessary to repeatedly raise and lower a string of casing a few feet for long periods in order to relieve the friction caused by pressure of the surrounding strata, and thus work a clear passage. This is known as 'spudding in' the casing. It requires continued reversing of the motor under heavy load, and is very well illustrated by the graphic record shown in Fig. 2, which was made on a 50-h.p. equipment. It is important that the motor should have ample margin in torque to accomplish this without overheating or stalling, as failure to free the string of casing compels the operator to continue with a smaller diameter. Occurrences of this kind would result in the minimum diameter being reached at too shallow a depth and thus render it impossible to continue drilling to the oil sand.

The other drilling operations are lighter work for the motor

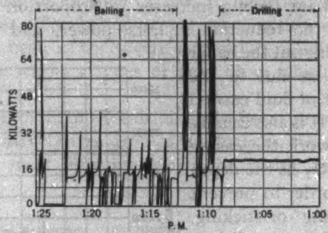


Fig. 3—Graphic Record of Power Required for Drilling and Bailing Work in a California Oil Well

as will be seen by a comparison of Figs. 2 and 3. The power demand from the motor to merely swing the tools during actual drilling by the cable-tool method is fairly steady, as Fig. 3 shows, but it is interesting to note that this demand becomes less as the well grows deeper. Fig. 4, which represents this

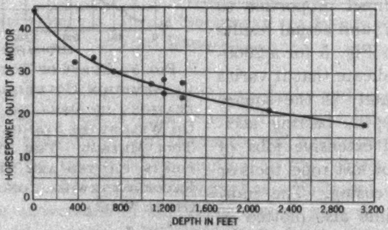


Fig. 4—Horse Power Required for Swinging Standard Cable Tools in Drilling a 3100-ft. Oil Well in West Virginia

fact, shows a curve plotted from readings taken during the various stages of drilling a 3100-ft. well. The point may be explained by the facts that as the well grows deeper the drilling tools used are smaller in diameter and lighter in weight, and a larger amount of water is usually carried in the hole.

After a well has reached a depth of 300 or 400 ft., the amount of energy required per hundred feet for all drilling operations by the standard method increases with the depth of the well. Although it has already been pointed out that the power necessary to swing the tools grows less, on the other hand the length of time required for bailing increases in proportion to the depth, with little or no reduction in horse power, and the dash-pot action in pulling out the bailer becomes greater due to the larger amount of fluid carried in the well. It is also usually necessary to work the casing more frequently as the depth increases, in order to prevent it from 'freezing' or sticking. Both of these conditions cause a considerable increase in energy consumption. Furthermore, progress becomes slower as the well deepens. Therefore considering all of these points, it is apparent that the kw-hr. consumption will increase more rapidly than in direct proportion to the depth, and actual results plotted in Fig. 5 for a 2060-ft. well indicate that it varies approximately as the square of the depth, barring accidents and extensive jobs of 'fishing' for lost rope, tools or damaged casing. The individual points also plotted in Fig. 5 represent the total power consumption recorded in drilling other wells of various depths. They check as closely as could be expected with the record for the 2060-ft. well at a corresponding depth. Under the usual conditions encountered, and without any great amount of bad luck in the drilling work, the average daily power consumption when the motor is in use, is about 230 kw-hrs., but it will vary on different days from approximately 135 to 400 kw-hr., depending upon what class of work is being done.

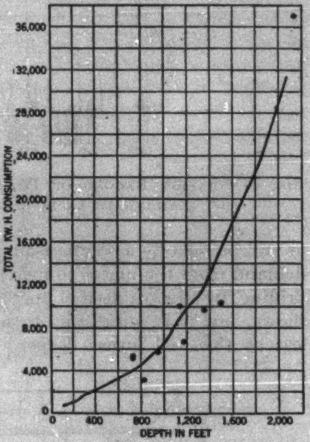


FIG. 5—CURVE OF TOTAL POWER CONSUMPTION COVERING ALL OPERATIONS IN DRILLING A 2060-FT. OIL WELL BY THE STANDARD CABLE-TOOL METHOD. THE INDIVIDUAL POINTS PLOTTED ARE THE TOTAL RECORDED KW-HR. ON VARIOUS OTHER WELLS

The most successful drilling motors now used in American oil fields are of the slip-ring induction type with secondary resistance control arranged for reversing duty. A capacity of 50 h.p. is usually sufficient for wells not exceeding 2500 ft. in depth, though cases have occurred where 75 h.p. was necessary on wells from 2000 to 2500 ft. in depth, as well as on the deeper ones. The belted arrangement with a countershaft has proved the best, as the severe service has rapidly put out of commission the various types of gear drive which have been tried.

In the cable-tool method of drilling, the beam must overspeed and allow a relatively free drop of the tools on the down stroke to obtain the most effective blow; the motor to accomplish this must therefore slow down on the up stroke and speed up on the down stroke. This is quite successfully accomplished by so proportioning the pulleys that the motor will have some secondary resistance in circuit when running at the correct drilling speed. There is also required a very fine adjustment of speed to make the movement of the beam accord with the natural period of vibration of the drilling line due to its elasticity. Failure to obtain the exact speed results in deadening the movement of the bit and may strain the line and rig dangerously. A suitably designed liquid rheostat would be an ideal method of control if it received the necessary attention and a good quality of water, but unfortunately neither of these can be given it under the usual conditions in the oil fields and so drum controllers have been adopted, connected as shown in Fig. 6. The main

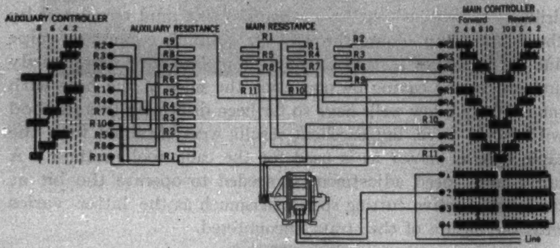


FIG. 6—CONNECTIONS FOR MOTOR EQUIPMENT FOR STANDARD CABLE-TOOL DRILLING

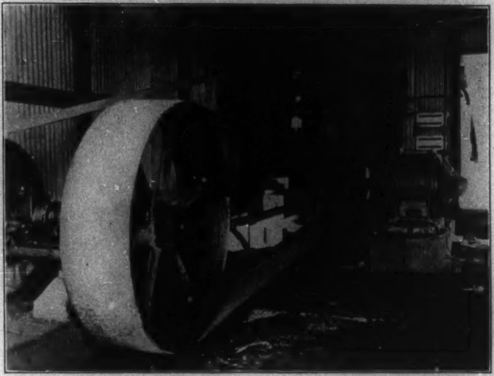
controller gives a coarse variation of speed and reverses the motor, and the auxiliary controller provides a means of obtaining fine speed control between the points on the main controller for either direction of rotation. These controllers are each operated by wire ropes extending to the headache-post in the derrick, the arrangement in this respect being similar to the method of throttle control employed with engine-driven rigs. A complete installation is shown in Fig. 7.

Drilling by the rotary method is accomplished by boring rather than by churning the hole. The drilling bit is supported at the lower end of a column of pipe which is held and rotated by a turntable. The latter is driven through a series of chains and gears. A hoisting drum, which is clutched in when desired, is also provided for handling the drilling stem and casing. The drillings are washed out by a stream of thin mud circulated by the 'slush-pump' down through the rotating column of pipe and up outside of it, thus causing the pipe to turn more easily and preventing caving by plastering the sides of the hole with mud. Only a few wells have so far been drilled by this method with motor drive, but excellent results were obtained with the same type of motor as is used for the cable-tool method. A fairly close speed adjustment is needed to operate the bit at the most effective cutting speed, inasmuch as the latter varies with the nature of the strata encountered.

PUMPING, PULLING AND CLEANING

Pumping is accomplished by means of a deep-well pump of the plunger type which is lowered on the end of a string of tubing to a sufficient depth to insure ample submersion. The plunger is operated by jointed iron or wooden rods extending down within the tubing and attached to the end of the walking-beam or to a pumping-jack operated from a central power-head. The flow of oil through the tubing to the surface is governed by suitable check valves in the barrel and plunger of the pump.

The rods and tubing must be frequently removed to clean out the well or to replace broken or worn parts, and the bull-wheel is then employed except where the use of pumping-jacks makes a portable hoist necessary. Rods are pulled with a single line, but a block and tackle with two or three lines is necessary for the tubing. Both are removed in lengths approximately 60 ft. long which usually consist of three 20 ft. sections screwed together. Bailing, light redrilling, washing or swabbing may be employed in the process of cleaning.



[TAYLOR]

FIG. 7—A 50-H.P. DRILLING MOTOR OPERATING CABLE-TOOLS ON A STANDARD CALIFORNIA RIG

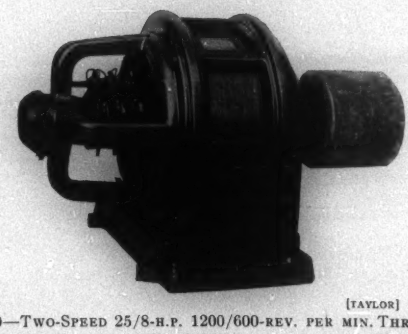


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FIG. 9—TWO-SPEED 25/8-H.P. 1200/600-REV. PER MIN. THREE-PHASE, 60-CYCLE, 440-VOLT OIL WELL MOTOR FOR PUMPING, PULLING AND CLEANING WELLS OF MODERATE DEPTH

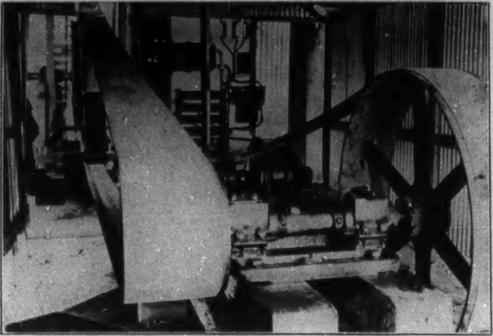

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FIG. 11—TYPICAL INSTALLATION OF A TWO-SPEED BELTED MOTOR FOR PUMPING, PULLING AND CLEANING WORK IN THE MIDWAY FIELD IN CALIFORNIA

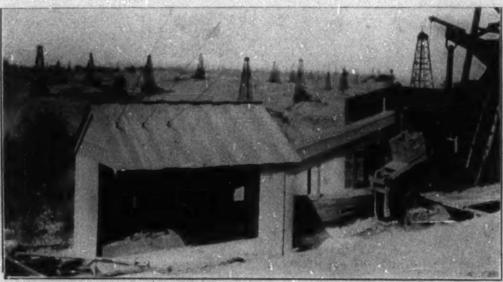

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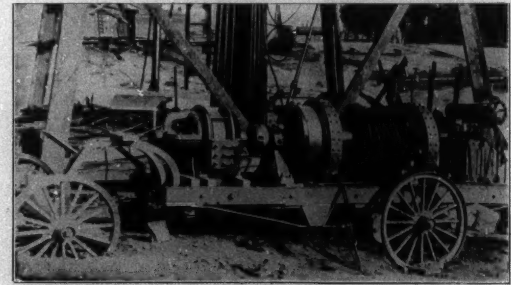
FIG. 12—BACK-GEARED OIL WELL MOTOR OF THE Y-DELTA TYPE IN THE KERN RIVER OIL FIELD IN CALIFORNIA



[TAYLOR]

FIG. 13—PORTABLE ELECTRIC HOIST USED FOR PULLING AND BAILING OIL WELLS PUMPED BY PUMPING JACKS IN THE KERN RIVER OIL FIELD IN CALIFORNIA

There is no apparent way to calculate the power necessary to pump a well which will give figures uniformly consistent with actual tests, because of the difficulty of determining the effect of varying well conditions. For instance, a large amount of sand in the oil will increase the power necessary to pump it, while on the other hand gas may be present which will help lift the oil. No numerical value can be placed on these conditions, so the motor capacity for this duty is determined largely by comparison with results obtained on other wells. Owing to the fact that the conditions are generally changeable, it is best to have some reserve motor capacity for pumping. The power input will vary from day to day and even from hour to hour, and may increase considerably in a short time when the well is sanding up. Such variations are not so common, however, where the troubles from sand are few.

The following summary of records from over 200 California oil wells pumped on the beam, gives an idea of the motor load for pumping alone:

Depth of wells	900 to 3100 ft., average 1430 ft.
Length of stroke	29 to 32 inches.
Strokes per min	20 to 30, average 24.
Diameter of tubing	3 inches.
Power required	1 to 5 h.p., ave. 3.5 to 4 h.p.

Exceptional wells in California have required as high as 16 to 17 h.p. at times. In Louisiana some heavy pumping wells have been encountered, one in the Evangeline field requiring the following:

Depth of pumping	1100 ft.
Length of stroke	30.5 in.
Strokes per min	40
Diameter of tubing	2.5 in.
Power required	9.5 h.p.

Another Louisiana well near the Caddo field gave test results as follows:

Depth of pumping	1000 ft.
Length of stroke	37.5 in.
Strokes per min	38.
Diameter of tubing	3 in.
Power required	17.5 h.p.

Compared with the California wells, these Louisiana wells have a longer stroke, higher speed, larger percentage of water and less gas in the oil, and therefore require more power. The

Caddo well, compared with the one in the Evangeline field, has a little lower speed, but larger tubing and less gas in the oil, and therefore takes more power. The depth of well does not usually appear to be a factor from which any logical conclusions can be drawn.

It is interesting to note that the counterweight which is now quite widely used on the walking-beam to counterbalance the weight of the rods in the well was originally installed to reduce the motor load fluctuation on each stroke, and was found to effect a saving in power as high as 22 per cent in some instances. Its use has since been extended in many cases to engine-driven rigs.

Where changes are frequently taking place in well conditions such as the rate of oil flow, the amount of sand with it, the amount of gas or water in the oil, the viscosity of the fluid or the condition of the pump itself, it is necessary to have a variable-speed motor to permit the operator to pump at what he considers is the maximum economical rate, which may be limited by the rate of oil flow or the rapidity with which the rods and plunger will drop in the oil on the down stroke. On the other hand there are many cases where squirrel-cage motors meet all the requirements of pumping.

Pulling the rods and tubing is ordinary hoisting work, carried on at a maximum speed of the band-wheel which may be from 50 per cent to 100 per cent higher than the pumping speed. It demands an intermittent motor output of from 35 to 80 h.p. or even higher under some circumstances. A high torque machine is therefore most suitable. The greatest heating of the motor occurs when handling rods, because of the very frequent reversals which may occur from three to five times a minute for an hour and a half to two hours at a time. Low armature inertia is consequently very desirable. Pulling tubing requires the highest torque and determines the size of motor necessary. The rating usually given the motor for this duty is merely nominal, as the maximum torque obtainable is the determining feature. The maximum load is that encountered when lifting together the rods and pump and the tubing full of oil. In determining the motor capacity it is convenient to use the following formula for the horse power required to lift tubing at a uniform rate of speed:

$$\text{h.p.} = \frac{W \times d \times N}{63{,}000 \times L}$$

in which W = weight lifted in lbs.
d = diameter of bull-wheel shaft in inches.
N = rev. per min. of bull-wheel.
L = number of lines used in the tackle.

The constant 63,000 is based on a mechanical efficiency of the rig of 50 per cent. This is a fair assumption for the majority of cases, as will be seen by reference to Fig. 8, which is an approximate efficiency curve plotted from the results of several tests. In addition to the value obtained from this formula there must remain a sufficient margin in torque for acceleration. This depends largely upon the flywheel effect of the motor armature, as the revolving parts of the rig have relatively small inertia.

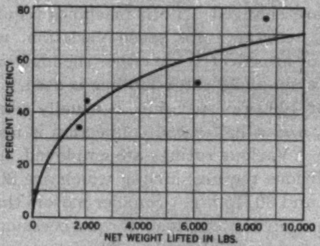


FIG. 8—APPROXIMATE MECHANICAL EFFICIENCY OF STANDARD AMERICAN OIL WELL RIG

Of the various operations of cleaning a well, swabbing requires the heaviest demand of power. The work consists of lowering a plunger into the well casing and then pulling it out. The plunger has a tight fit in the casing so that the suction thus produced draws the sand out of the perforations at the bottom and thus clears the oil passages. The operation may be performed for several hours at the rate of two to four times per hour, each hoisting trip of the swab requiring several minutes. Peak inputs to the motor from 40 to nearly 70 kw. have been recorded in this work.

The total monthly power consumption for all the work of pumping, pulling and cleaning a well will vary from approximately 1350 to 6000 kw-hr. but the average is about 2100 kw- hr.

The necessity of employing a single motor for all of the work of pumping, pulling and cleaning is due chiefly to two reasons; first, the impracticability of using a portable hoisting equipment for wells that may have to be pulled every few days, particularly where the country is rough; second, the desire of a great majority of operators to have a machine which will take the place of the steam engine with little or no change in the method of operation.

The most successful and most widely used induction motors for this duty are of two types, the 'Y-delta' and the two-speed. Except in special instances both are of the slip-ring type, the former being designed for changing the normal capacity by a change in stator connections made by a suitable switch, this not, however, affecting the speed; the latter has a pole-changing switch mounted on the frame by means of which both the speed and capacity are changed. Both machines require a controller and secondary resistance for speed variation, which with the two-speed motor are effective on either the high or the low-speed connection, as a six-phase rotor winding is used. A synchronous speed of 900 or 1200 rev. per min. is usually selected for either type of motor, and a half-speed connection is used on the two-speed machine. Various ratings are employed, depending upon what the conditions require, among which are 20/7 h.p., 20/10 h.p., 25/8 h.p. and 30/15 h.p. Smaller motors than these generally cannot develop the overload torque occasionally necessary in emergencies on nearly all wells. The low capacity is used for little else but pumping, and the design is therefore made for as high an efficiency as possible on this connection without sacrificing the required torque on the higher rating. The maximum momentary capacity is from 300 per cent to 450 per cent of the high rating, but full-load efficiencies of from 75 per cent to 85 per cent, and power factors nearly as good, are nevertheless obtained at full load on pumping duty.

With the Y-delta motor, a high speed for pulling can be obtained only by changing the pulley or by lagging up the bull-wheel shaft to a large diameter. Few operators care to be bothered with the pulleys, while there are some who will not consider the other method because of the increased strain on parts of the rig. Lagging the bull-wheel shaft furthermore does not speed up the sand-reel, so bailing must be done very slowly. But where the operator will use a lagged shaft and has no sand-reel, the Y-delta motor does very well, except for one point which in many cases is important. It is very often the practise to 'shake-up' a well to free the pump valves from sand and thus avoid pulling the rods and tubing. This is accomplished by increasing the speed of the walking-beam for a few minutes, but there is no practical way to do so with this type of motor, as the time required to change pulleys makes this method out of the question. The two-speed slip-ring motor, as may readily be seen, overcomes all these difficulties and has therefore received wide-spread approval by practical oil men. One of these motors is illustrated in Fig. 9.

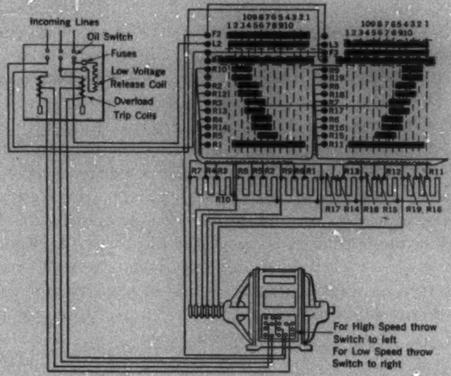

Incoming Lines
Oil Switch
Fuses
Low Voltage Release Coil
Overload Trip Coils
10 9 8 7 6 5 4 3 2 1
1 2 3 4 5 6 7 8 9 10
F2
L2
L3
F3
R10
R2
R12
R3
R13
R4
R14
R5
R1
R9
R19
R8
R18
R7
R17
R6
R16
R15
R11
R7 R4 R3
R8 R5 R2
R9 R6 R1
R13
R12
R11
R10
R17 R14 R18 R15 R19 R16
For High Speed throw Switch to left
For Low Speed throw Switch to right

FIG. 10—CONNECTIONS FOR TWO-SPEED MOTOR EQUIPMENT FOR PUMPING, PULLING AND CLEANING DUTY

The connections of the two-speed equipment in Fig. 10 show the method of protecting the double-rated motors by double-wound overload trip coils on the oil switch, which are so interlocked by connections with the switch on the motor that proper protection is automatically obtained. The controller is operated by a rope wheel from the derrick as described for the drilling motor.

While the majority of installations use a belted motor with countershaft, there are many back-geared machines in operation, the two arrangements being shown in Figs. 11 and 12. Oil men display a preference for the former, but most of the gear noise has been eliminated on the most recent back-geared installations by the use of cloth pinions, and it is anticipated that more of these will be used in the future.

The use of separate motors for pumping and pulling work requires little comment, as it is a simple proposition to select machines with the proper characteristics. The hoist motor must be portable, and either it may be coupled to a hoist mounted on a truck as shown in Fig. 13, or the motor equipment may alone be portable and designed to be belted to the countershaft at each well. Both methods are successfully used. The complete portable hoist is better adapted for wells pumped by pumping-jacks.

Pumping-jacks are operated together from a central point, the reciprocating motion being obtained by eccentrics or cranks which are belt driven. Motors have been applied to a large number, but no features of unusual interest are involved, as the duty is non-reversing and a friction-clutch is frequently used for starting the load. It is an interesting comparison with the individually driven well to note that the power required for jack-rig pumping averages approximately 2.5 h.p. per well and the average consumption is from 30 to 45 kw-hr. per day. The use of jacks has more than cut the power bill in two in some cases, but they are considered advisable only when the well production falls very low, as their use causes a loss of from 15 per cent to 25 per cent in production because of the impossibility of running each well at its most advantageous speed.

Oil well motors have been used in eastern United States fields for the past twelve years, but active interest was not taken in them in California and the middle west until 1910. The conditions encountered in those fields required the development of the equipments described in this paper, which with little or no change can successfully meet any conditions so far encountered in this country. During the first three years over a thousand wells were electrified in California alone. Although very little development work has taken place in the fields during the past two years due to the very low market price of oil, it is estimated that there are between 1500 and 2000 electrically-operated oil wells in the United States at the present time.

No attempt has been made in this paper to give comparative operating costs, as a considerable amount of valuable data on that subject has already been published and is readily available to those interested.

DISCUSSION ON "MOTOR EQUIPMENTS FOR THE RECOVERY OF PETROLEUM" (TAYLOR), CLEVELAND, OHIO, JUNE 27, 1916.

F. Woodbury: About five or six years ago I was associated in the pioneer work near Los Angeles where some of these oil well motors were developed. We had considerable trouble owing to the prejudice of the operators against the apparatus, as mentioned by Mr. Taylor. They endeavored to discredit the motors by running full speed and reversing as fast as they could, doing everything possible to burn them out. However, in this they were not very successful, and we finally succeeded in successfully installing several motors.

The largest saving to be effected by motor operation is with producing wells which require pumping. Wells in process of drilling are comparatively few, so it is questionable if much is to be gained by using motors for this severe duty. An example of what was saved on the property where the development work took place is herewith given. Before electrification all of the natural gas on the property plus 30 to 50 barrels of oil was burned per day to produce the necessary steam for the pumping engines. After equipping 15 or 20 wells with pumping motors it was found no longer necessary to burn any oil, and there was an excess of natural gas. Electric power was supplied from a small plant receiving steam from the same boilers that were used to supply the pumping motors.

Mr. Taylor notes that there are many instances where it is hard to get motors installed due to local conditions not being suitable. This is quite true in cases where there is ample natural gas and the prospective customer is using gas engines. In other cases where crude oil is used for steam generation and the steam is piped considerable distances, large savings can be made by using motors.

A. M. Dudley: There is one fact that Mr. Taylor has not dwelt on, and that is the greater convenience of the electric motor. In such territories as the oil fields of West Virginia the hauling of a heavy steam boiler over the rough country is a serious problem. Six horses and even eight are often employed. You can readily appreciate that a motor occupying possibly 4 or 5 cubic feet and weighing not over 700 or 800 pounds is a most acceptable substitute.

Another point, is the great flexibility of the induction motor in the performance of any and all classes of work. It has been brought to your attention in connection with the paper on reversing rolling mills that in many cases the limiting factor of the d-c. motor is commutation. The induction motor has no commutation and for short-time loads is limited practically only by the maximum torque it will develop. Mr. Taylor also shows that by connecting Y and Δ, a maximum torque practically three times as great may be developed where needed for short periods in cleaning and "pulling." and that this is coupled with high efficiency when pumping continuously for days at a stretch. Another point brought out, is the possibility of connecting the same winding for two speeds and thus further adapting the motor to its work. From many points this is almost an ideal combination of motor and tool characteristics.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 27, 1916.

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REPORT OF THE TRANSMISSION COMMITTEE

I—DATA FROM OPERATING PLANTS ON THE EFFECT OF ALTITUDE ON THE OPERATING TEMPERATURE RISE OF ELECTRICAL APPARATUS

BY PERCY H. THOMAS, CHAIRMAN

RECOGNIZING the absence of conclusive data on the altitude correction to be applied to the temperature rise of electrical apparatus, and further the lack of uniformity of the general practise as well as the frequent entire omission of the correction, the Transmission Committee undertook the collection of data as to the opinion and practise of operating engineers and sent a list of questions to 150 companies and individuals.

The information received is herein summarized and discussed. It should be noted that no effort has been made by the Committee to make laboratory tests or scientific investigations—nor does the Transmission Committee offer any definite rule of correction, for this is the function of the Standards Committee. The data collected are presented as information for the use of any committee or individuals who may find it helpful.

Thirty-one replies were received. Of these 15 were from plants operating apparatus at 5000 ft. (1524 m.) altitude or higher, which are here called high-altitude plants. Of these 15 high altitude plants six make no correction for altitude and six have noticed no effect of altitude. Comments of more or less interest have been received from some of the above and are here summarized.

From W. N. Clark, Arkansas Valley Ry. Lt. and Pr. Co., Canon City, Colorado.

Altitude 9000 to 10,000 ft. (2743 to 3048 m.)

Take account of altitude both in purchasing and loading transformers. Have no definite rule for correction but have by experience determined which design of transformers operate satisfactorily. The transformers in question are step-down transformers in the Cripple Creek district, ranging in capacity from 100 to 900 kw.

We have noted that on some of the more modern closely rated equipment that the temperature remains high. This does not apply to some of the older more liberally rated apparatus such as generators and transformers.

Six 200 kv-a., oil-insulated, self-cooled transformers required water cooling coils to prevent constant excess temperature at rated capacity, however, part of the cause was poor circulation of air in and out of building.

The correction factor is not large. I think it should be made. I think the capacity should be rated lower for the higher altitudes, something similar to the method of rating air compressors.

Lightning discharges take place over longer setting of horn-gap arresters.

From W. O. Vickery, The Trinidad Electric Transmission. Railway and Gas Co., Trinidad, Colo.

Altitude 6000 to 7000 ft. (1828 to 2133 m.)

No account taken of altitude up to spring of 1915.

No rules adopted, but it is thought best in future to specify temperature and altitude in purchasing electrical apparatus.

From general observations it is noted that oil-insulated, self-cooled transformers run approximately 10 per cent higher than manufacturer's guarantee. This is also noted on induction motors, except that induction motors run only about 7 per cent higher than guarantees. Generators seem to operate about 5 to 6 per cent higher than guaranteed rating of temperature.

Nothing definite. However, the loss of the coils in a 2000-kw. turbo-armature we believe could be partly attributed to higher temperature resulting from high altitude.

Generally speaking, increased temperature at high altitudes was called to our attention in the spring of 1915. Since that time, observations have been made, which lead us to believe that there is considerable increase in temperatures of electrical apparatus when operating at altitudes of 7000 to 10,000 ft. (2133 to 3048 m.) above sea level, and it is believed rules should be formulated covering such apparatus when making purchases.

From R. W. Toel, Chf. Engr., Denver Tramway Co., Denver, Colo.

Altitude 5280 ft. (1609 m.)

Take account of altitude in loading transformers.

Air transformers have been noticed to operate from 10 to 12 deg. cent. higher than manufacturers specifications under given load conditions.

Air transformers have failed due to high temperatures, operating under normal conditions.

Should think that a correction factor should be made of at least 10 deg. cent. higher than temperature rating for apparatus used at sea level under same operating conditions.

From J. H. Rider, 8 Queen Anne's Gate, Westminster, S. W. London.

Altitude 6000 ft. (1828 m.), neighborhood of Johannesburg, So. Africa.

Takes account of altitude in generators, motors and transformers both in purchasing and loading apparatus.

To secure a maximum temperature rise of 35 deg. cent. in motors with an ambient air temperature of 35 deg. cent., motors must not exceed a temperature rise of 30 deg. cent. with an ambient air temperature of 25 deg. cent.

The neighborhood of Johannesburg is at an altitude of 6000 feet above sea level, and from experience there I have had to adopt the following basis for the temperature of the motors, namely, a maximum temperature rise of 35 deg. cent. with the surrounding air at a temperature of 35 deg. cent.

As the plant has to be tested at the maker's works at sea level, the prescribed limits for such a test are a temperature rise of 30 deg. cent. with the surrounding air at a temperature of 25 deg. cent. as experience has shown that these figures correspond very closely indeed with the limits for the higher altitudes.

I have had considerable difficulty with some manufacturers in getting them to design their plant for what appears to them to be abnormally low temperature rises at sea level, but by persistence have succeeded now in getting those figures without difficulty.

Yes; correction should be made for altitude.

From K. C. Randall, 133 *Dewey Avenue, Edgewood Park, Pa.*

Have never allowed nor encountered requests for allowance in rating of apparatus because of expected operation at high elevations.

Have never heard of instances where loading is in any way controlled by elevation.

I believe that in general the extra complications from introducing corrections for elevation will be largely a paper burden and in general of no material significance, particularly as standard apparatus should be employed as far as possible and that any acknowledgment of the effect of elevation will only add to the expense of both consumer and manufacturer without any return to either. This is particularly true, as the wide range of conditions of installation, ventilation and operation will have in general much more bearing on operating conditions than variation in elevation.

From Charles S. Ruffner, Genl. Mgr., The Electric Company of Missouri, Webster Grove, Mo.

Confining the questions strictly to the effect of air pressure on thermal conditions, might omit considering other factors in the cooling of apparatus at high altitudes. The prevailing lower temperatures at high altitudes, with particular reference to the invariably cool nights, might, in practise entirely offset any difficulty with the volumetric thermal capacity of the air.

Personally I have not noted any cooling difficulties in any apparatus operated at high altitudes arising from the rare atmospheres, and I cannot think of any important practical question in that connection excepting only in the design of forced ventilating systems. In that case, the apparatus being cooled by air blast might require a larger volume of free air. Such a case has not, however, come under my observation.

A few simple experiments on the rate of transfer of heat from any substance to atmosphere of different pressure might determine the quantity of air at different pressures required for equivalent cooling effects.

From P. M. Downing, Chf. Engr., Hydroelectric Dept., Pacific Gas and Elec. Co., San Francisco, Cal.

In this connection I might say that the effect of altitude on the temperature reading of electrical apparatus, is something that we have never considered of great importance. The writer has had personal experience in the operation of such apparatus at altitudes ranging from sea level to 8500 ft. (2590 m.), and although I have never made any careful tests, have never been able by casual observation to notice any change in the heating of the apparatus.

From C. D. Gray, Asst. Elec. Engr., J. G. White Engineering Corporation, 43 *Exchange Place, New York.*

Our personal opinion is that if the altitude is over 6000 or 8000 ft. (1828 or 2438 m.) some attention should be given to this matter and we would probably specify about 5 deg. lower temperature than for a machine used at lower altitudes.

From J. F. Dostal, Genl. Mgr., The Colorado Springs Light, Heat and Power Co.

Altitude 6000 and 7000 ft. (1828 and 2133 m.)

Take no account of altitude either in purchasing or loading apparatus.

Feel that some allowance should be made. Have noticed that fans run hot.

From E. R. Davis, Genl. Mgr., Pacific Light and Power Corporation, Los Angeles, Cal.

Altitude 5000 ft. (1524 m.)

To yours of July 26th covering data sheet for references to effect of altitude in temperature of electrical apparatus, the replies to all the questions except the first may be summed up in the statement that this company is not taking any account of the effect of altitude on operating apparatus and has no observations or tests on record which would have any bearing on the matter.

The above data indicate clearly that most engineers operating at altitudes over 5000 ft. (1524 m.) have ignored the question of the effect of altitude on the operating temperature of electrical apparatus. This appears rather to be because of lack of tests on their own apparatus and lack of convincing engineering data in any form. As at most, the effect of altitude involves a limitation of only a few per cent and as apparatus is seldom loaded to exactly 100 per cent of capacity, the point of view is natural. However, at the higher altitudes where engineers have made an effort to look into the subject they usually conclude that a correction should be made.

While in most cases the altitude correction is not important, there are some where it is of great importance, for example to such a company as the Chile Exploration Company which expects to have 100,000 kw. of transformers and motors at 9000 ft. (2743 m.) altitude, much of which will be carefully rated, or as the Cerro de Pasco Mining Co. with apparatus at the extreme altitude of 14,000 ft. (4267 m.)

Obviously the data collected by the committee form no basis for the drawing of a definite altitude correction, and the collection of data was not undertaken with that in view. It serves however to show the attitude of engineers in general on this question and thus it is of considerable interest.

Two of the replies above quoted are to the effect that their authors considered that the altitude correction is not of magnitude enough or sufficiently precise to warrant a formal rule.

Two of the replies included certain matters not strictly pertinent to the subject of the inquiry but still cognate and of some interest, they are appended below.

From J. H. Rider, 8 *Queen Anne's Gate, Westminster, S. W., London.*

One of the things which no manufacturer ever pays attention to is that the temperature rises of generators and motors tend to increase as time goes on, even with the same load. This is because the first temperature tests are made with the machine in a new and clean condition, with all ventilating passages in good order. During working, however, it is impossible to keep dirt from collecting in the air passages, and so the ventilating facilities get worse and worse, as time goes on.

It is quite impracticable to clean out the ventilating spaces without dismantling and then rebuilding the whole machine, which, in practise, is impossible, as a user is entitled to expect his machine to run satisfactorily for very many years, if he gives proper attention to the bearings, brushes, etc.

The above point, perhaps, does not concern only motors which are intended to work at high altitudes, but it shows that the test temperature of such machines at sea level must be quite as low as those which are fixed upon if satisfactory after-running is to be obtained.

If your committee, therefore, could both fix upon a standard for temperature tests at sea level to give reasonable working temperatures at high altitudes, and also make such sea level figures low enough to provide for the gradual clogging of the air passages, you will have done a very great work.

From R. S. Masson, 705 *Security Building, Los Angeles, Cal.*

I was much interested in your letter about the effect of altitude on the temperature rise of electrical apparatus. I have been determining for a number of years in my own mind that humidity was the real nigger in this altitude woodpile. In other words, I am of the opinion that altitude as such does not effect the cooling capacity of the air to any material extent, but that humidity, which may be directly related to altitude in some instances, causes the trouble.

When the writer undertook to operate certain motor-generator sets in Phoenix, Arizona, about three weeks ago, it was found that the machines ran very much above their testing temperature and, after accusing power factor and other common enemies, it was found that there must be another cause. Phoenix was then a close neighbor to great areas of desert and the average humidity was so low that the air was practically dry. We then tackled this problem of constructing a humidor which, in effect, was not much different from any of the attempts which have been made by power house operators; ours having the form of water screens rising out of a water bath like the old overshot water wheel with the air flowing through these screens. This air was conducted through canvas housings to the ends of the motor generator sets and allowed to flow out through the stators, without changing the machines themselves at all. The effect was very marked and increased the capacity of the normal rated 600-kw. machines about 125 to 150 kw. at the same temperature rise.

Referring then to the problem as presented in your letter. Here was a machine located at an elevation of about 800 ft. (243 m.) which was having all of the troubles that had previously been experienced at altitudes of 8000 and 10,000 ft. (2438 to 3048 m.) It would be interesting to have some of the operators of plants in high altitudes test out this method of cooling the air to see if they cannot put their machines on the same basis as the sea level machines.

This test which we made, however, was not quite true, as the effect of blowing the air through these water screens was to actually cool the air by evaporating the water and, of course, the machine was practically running in a lower temperature. In order to make a true test of the effect of humidity alone it would be necessary to re-heat the air, after it has accumulated moisture, to the temperature of ordinary air. This test I will be glad to make, if it would be of any interest, as it can be done in the said Phoenix motor-generator apparatus without inconvenience or unnecessary delay.

The above extracts are self explanatory.

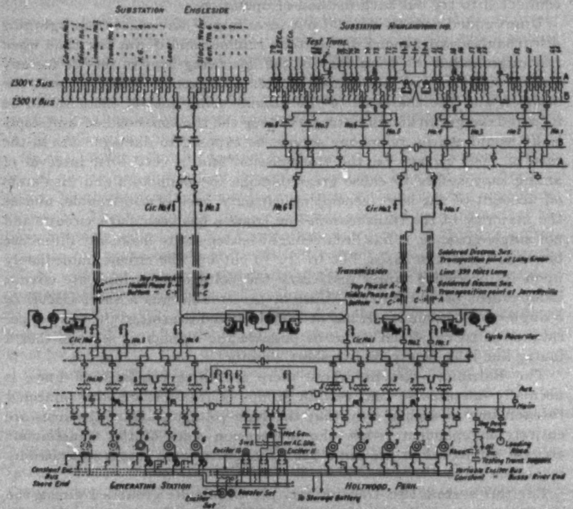
II—EXPERIENCE WITH GROUNDED NEUTRAL ON HIGH-TENSION TRANSMISSION LINES

To secure a comparison of the experiences of various companies operating high-tension systems with grounded neutrals, the Transmission Committee sent an information blank to a large number of power companies and the present report covers the information secured.

It is believed that the various replies can be best offered by printing verbatim or in rearranged form the more important reports; comments will then be made.

From the Pennsylvania Water and Power Company, Mr. A. Bang, Testing Engineer.

The Pennsylvania Water and Power Company operates a hydroelectric plant located at Holtwood, Pa. The generating capacity of this plant is at present about 83,500 kw.; the current is three-phase, 25 cycles, and generated at 11,000 volts. This voltage is stepped up to 70,000 volts by means of three-phase transformers, which are delta connected on the low-tension side and star connected on the high-tension side.


SUBSTATION ENGLESIDE
2300 V. Bus.
2300 V. Bus
Trans. No.
M.G.
Local
Stock Water
Gen. No.
SUBSTATION
Test Trans.
A
B
No.8
No.7
No.6
No.5
No.4
No.3
No.2
No.1
Cir. No.4
No.3
No.6
Cir. No.2
No.1
Soldered Discons. Sws.
Transposition point at Long Green
Transmission
Line 39 Miles Long
Soldered Discons. Sws.
Transposition point at Jerrettsville
Top Phase A
Middle Phase B
Bottom – C
Cycle Recorder
Cir. No.1
No.2
No.1
Cir. No.5
No.3
No.4
No.10
Aux.
Main
Mot. Gen.
or A.C. Dis.
Exciter II
Exciter I
Loading Rheo.
Testing Trans.
Constant Exc. Bus
Shore End
GENERATING STATION
Exciter Set
Booster Set
To Storage Battery
HOLTWOOD, PENN.
Variable Exciter Bus
Constant – Busses River End

ONE-LINE WIRING DIAGRAM OF GENERATING STATION—TRANSMISSION AND SUBSTATIONS

The bulk of this power is transmitted to Baltimore, Maryland, through three 70,000-volt 40-mile (64-km.) long transmission circuits. At the terminal station in Baltimore the voltage is stepped down from 60,000 volts to 13,200 volts by means of three-phase transformers, delta connected on the high-tension side and star connected on the low-tension side. This power is then distributed through a 13,000-volt underground cable system to a number of substations located in Baltimore.

A minor part of the power generated at Holtwood is transmitted at 70,000 volts to Lancaster, Pa., where the voltage is stepped down to 2300 volts through single-phase transformers connected in open delta.

The accompanying one-line wiring diagram and tabulations of the resistances and reactances of the various apparatus used in the generation and transmission of power will give an idea of the size and characteristics of the plant and transmission system.*

The transmission of power to Baltimore was started in the autumn of 1910 and to Lancaster in the autumn of 1913.

Both of these systems are run with the neutral grounded at the power house only. The Lancaster system has always been run grounded; the Baltimore system has been grounded all the time except for a short interval during the summer of 1911 when the grounds were temporarily disconnected to try out such method of operation.

Ungrounded connections did not seem to give any relief from lightning disturbances experienced during that summer and it was felt that when run ungrounded the possibility of the line being kept in service for any length of time, with one phase accidentally grounded and without the location and the character of the ground being known, there would be incurred danger to life and property along the transmission line and especially would nearby telephone service be exposed to damage. As in the case of *short circuits* on the transmission line, a very brief interval of arcing may suffice to cause great damage to conductors and insulators on account of the large generating capacity back of the trouble, and as the majority of the transmission-line trouble has been short circuits and not single grounds, it has been thought better not to make any difference between these two cases, but to try to cut out the circuit immediately upon its becoming faulty and carry the voltage on a duplicate circuit, independent of whether the cause of the trouble was a short circuit or a single-phase ground. It has been endeavored to arrange the relay apparatus so as to cut down as far as possible the number of seconds that a faulty line may be exposed to short circuits.

The Baltimore system, where there are three transmission lines, is normally operated so that certain groups of transformers are connected to each line in such a way that the high-voltage sides of the lines are entirely independent, while the low-tension sides of the transformers are all connected to the same bus; though to some extent separated by reactance coils.

For this system two transformers per circuit are grounded during the lightning season, whenever possible. The object of this arrangement is to obtain a heavier rush of current on that transmission line on which the spill-over occurs so as to operate special series relays used in connection with the Nicholson arc extinguisher which is installed on these lines. Tests indicate that there is no harmful interchange of current when the neutrals of two transformers in parallel are grounded, even when these transformers are of different capacity or made by different manufacturers.

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*For further descriptive details of this plant and particularly the transmission lines see: (1) Engineering Data Relating to High-Tension Transmission Systems, Sub-committee Report. A. I. E. E. TRANS., Vol. XXXIII, 1914, p. 1013. (2) Foundations for Transmission-Line Towers and Erection of Towers, by J. A. Walls, A. I. E. E. TRANS., Vol. XXXIV, 1915, p. 1201. (3) Four Year's Operating Experience on a High-Tension Transmission Line by A. Bang, A. I. E. E. TRANS., Vol. XXXIV, 1915, p. 1243.

Outside of the lightning season only one transformer per circuit is grounded as a matter of switching convenience.

On the Lancaster system only one transformer is normally used and consequently only one grounded.

At present the transformers are grounded through metallic resistances. The system was originally run dead grounded from the neutral point of one transformer per circuit. It was thought that the ground short-circuit currents produced thereby were too heavy, and that some of the early transformer breakdowns might have been due to this cause, so a resistance was inserted between transformer and neutral ground. From tests and calculations made later it would appear that even with the present reactance coils the current that one single dead grounded transformer can receive may be dangerous, but that this would not be the case if several transformers of the same bank were grounded at the same time and that with all the transformers grounded at the same time, it would be quite possible to run safely without ground resistance. However, this latter arrangement has not yet been tried out as a practical operating condition on the high-tension transmission lines.

On the 13,000-volt cable system in Baltimore the arrangement of having all the transformers dead grounded has been adopted and been in service for the last year and a half apparently without causing any inconvenience. The reason why this system was adopted here instead of the former system where only one transformer was grounded through a resistance was to make certain of a sufficient current on a ground to trip the relays, which on account of the desire to get selective action of the relays between various substations, are set for rather high tripping current. The condition of running entirely ungrounded on the cable system has never been tried but would hardly be of any great benefit, as most of the cable troubles apparently start between conductors, and not as grounds.

The first resistance tried for the transformers at the power house were concrete blocks, which proved unreliable on account of lack of constancy in resistance and because they gave rise to arcing when voltage was built up on them.

Cast-iron grid resistances were then substituted and have been satisfactory on the whole. The difficulties experienced with them are their limited heat capacity in the case of some ground hanging on unexpectedly long, and also on account of the occasional failure of the insulation between grids.

The ground connections used at the Holtwood power house are of different types. In the main they consist of:

(a) Several copper plates buried in the mud in the forebay.

(b) Twenty-four 1½-in. (38-mm.) galvanized iron pipes driven 9 ft. (2.7 m.) in the wet earth in the neighborhood of the first tower of the transmission line.

(c) Several heavy castings lowered in the tail race (the connections to some of these latter were accidentally torn loose and have not been restored.)

(d) Besides the above artificial grounds an effort has been made to tie in all metal parts in the power house with the ground system and to tie in specially with such metal parts as are in direct connection with the river water, as for example, head gates and racks. The power house grounds are furthermore tied in with the overhead ground wires on the transmission lines. All these connections are made solid and, therefore, do not easily lend themselves to regular tests; such tests are consequently not made, but occasionally inspections are made of the cables connecting with the ground plates, etc., to see that such connections have not been torn loose.

From time to time other tests have been made on the individual "ground" and some of the results are as follows:

(1) Forebay ground consisting of four interconnected copper plates, 2 ft. 6 in. (82.2 cm.) by 3/32 in. (2.38 mm.), buried in the mud, 0.04 ohms.

(2) Large castings in the tail race (three in multiple) 4.4 ohms.

(3) Individual tower grounds on the transmission line, stubs set in concrete but grounded by means of a paragon cone and measurements taken with the ground wire removed, 150 to 350 ohms.

(4) Recent measurements taken between all the power house grounds connected in multiple, and a similar system of grounds at the substation 40 miles (64.3 km.) away, showed a combined resistance of about 2 ohms, though it is not possible to say how much of this is located at the power house and how much at the substation.

The current in the neutral is used to secure selective relay operation in the following way:

One or two of the transformers of each group supplying a transmission circuit have their neutrals grounded at the power house. The ground current from any transmission circuit will, therefore, pass through the neutral ground resistance of that circuit, and this ground current acts through a current transformer on a relay, which latter opens the low-tension switches of the transformers connected at the power house to that particular transmission circuit. This system, from the very start of the plant, has given satisfaction in respect to selective action on grounds and is considered as one of the main advantages of running the system with a grounded neutral. It is to be noted that the above relay action is quite distinct from the action obtained with the Nicholson arc extinguisher, the latter requiring a heavy ground current to energize its series relay, while the former does not require heavy current for the operation of its relay.

The current obtained when an accidental ground takes place on the line will naturally vary greatly, depending upon

(a) The character of the ground, *i. e.*, whether it in itself contains appreciable ohmic resistance or not; but even if we consider that we are dealing only with "dead grounds" the amount of current will vary with the total amount of impedance in the circuit and will, therefore, depend on

(b) The amount of resistance contained in the grid iron rheostat used in the neutral of the transformer;

(c) The number of transformers grounded;

(d) The generator capacity behind the ground;

(e) The location of the ground, *i. e.*, whether near the substation or power house;

(f) Furthermore the ground current will vary with time, being greater during the first few cycles and then gradually dying out, due to the de-magnetizing of the generators and the heating of resistance grids, in the neutral.

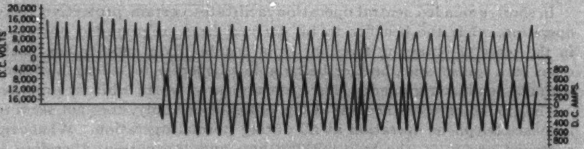
In the following tabulation some results are given of calculations of the ground current as based on a number of oscillograms taken on the P. W. & P. Co's. system to determine the exact value of ground currents for different locations and conditions.

INITIAL RUSH OF CURRENT WHICH TAKES PLACE ON THE P. W. & P. CO'S. SYSTEM WHEN A LINE IS GROUNDED.

Baltimore—Holtwood Circuit

Number of generators used	Number of transformers grounded	Location of ground	Initial ground current	Ohmic res. in neutral rheo. per transformer
3	2	At power house	656 amp.	58.4ohms
		At sub-station	430 "	58.4 "
3	1	At power-house	380 "	58.4 "
		At sub-station	290 "	58.4 "
Holtwood—Lancaster Line				
1	1	At power house	280 amp.	116 ohms

The accompanying sample oscillogram illustrates the characteristics of such a ground current.



"B" Phase Ground in Piney Island—Gen. 1 and 2—Trans. 1 and 2—Ground Stacks 1 and 2—Voltage 10,500 Volts Before Test

The operating record for 1915 of the P. W. & P. Co's. system is given below, as far as single grounds are concerned without accompanying short circuits. It should be noted that in *all* cases the grounds were cleared without serious interference with the operation of the system and that none of them lasted more than four seconds. (Only in one case was a small part of the load lost and then only for a few minutes.)

NUMBER OF SINGLE-WIRE GROUNDS ON THE HOLTWOOD-BALTIMORE CIRCUITS, 1915, THEIR CAUSES AND THE METHODS BY WHICH THEY WERE CLEARED.

	Cleared of itself without relay action	Cleared by arc extinguisher	Cleared by interlocking relay	Cleared by hand	Total
Lightning	1	4	1	0	6
Sleet	0	0	0	0	0
Birds	..	..	6	..	6
Insulator failure	0	0	0	0	0
Total	1	4	7	0	12

Grounded operation is preferred as enabling a faulty line to be cut out of service promptly so as to minimize damage to equipment or damage to property or life of outsiders, specially since a short period of operation ungrounded did not prove of benefit in reducing disturbances from lightning spillovers. An advantage claimed for an ungrounded system is that it permits service to be continued in the event of failure of insulators on one conductor, but it is rare to have a sufficient number of suspension units of one insulator string on a steel tower line damaged simultaneously to an extent to cause a permanent ground at that insulator, so that, as far as the circuits of the Pennsylvania Water and Power Company go, the advantage above claimed is of slight importance. The grounding of the neutrals should under certain conditions, result in subjecting the insulation of the high-tension circuit to a stress lower than that obtaining when running ungrounded. However, since the effort has been made on this company's lines to insulate rather against lightning than against generator voltage (insulation for 110,000 volts working pressure being in use on a circuit having a working voltage of but 70,000 volts) such lower stressing of the insulators has not been considered a factor of importance.

In short, grounded neutral operation facilitates certain protective relay operation, while the benefits to be derived from ungrounded operation in the sense of obtaining freedom from trouble from momentary flashovers on a transmission line, or being able to operate for a length of time with one conductor grounded, have not appeared worth while in practise.

The grounding of the neutral at the power house only, does not seem to influence telephone operation at all during normal operation. Whenever a ground occurs on the transmission line and the current therefore is flowing back through the soil to the station, very serious interference with telephone conversations will be observed, but this condition will as mentioned ordinarily not last for more than a few seconds.

Outside the lightning season, both high-tension grounds and short-circuits are cleared by overload relays and ground relays at the power house, and reverse-current relays at the substation. During the lightning season the Nicholson arc extinguisher equipment is put in service and given the first chance to extinguish flashovers on the line. In case this apparatus and the relay arrangement described both fail to clear the trouble, the field is destroyed automatically on all the generators at the power house and brought back again after 1.5 seconds.

As to the chief causes of interruptions, an idea will be had from the tabulation below, which gives a record for the year 1915 of all the disturbances on the Pennsylvania Water and Power Company's system as far as they had their origin on one of the three Baltimore circuits. This record includes both grounds and short circuits. The disturbances are divided into three groups, depending on the momentary loss of load resulting from them, *i. e.*, total interruption (T. I.), partial interruption (P. I.), and mere voltage or frequency disturbances (V. D.).

Operating record for the Holtwood-Baltimore transmission line:

Cause	T. I.	P. I.	V. D.	Total
Lightning................	3	13	8	24
Defective insulators........	..	1	..	1
Sleet on cables............	..	..	2	2
Birds on line.............	..	..	8	8
Wires blown together......	..	1	..	1
Defective cable clamp.....	1	..	..	1
Lineman's mistake........	..	1	..	1

Only a current less than one ampere flows normally in the neutral connection. The frequency of this current is not known.

AVERAGE REACTANCE AND RESISTANCE OF BUS REACTANCE COILS USED IN SHORT-CIRCUIT CALCULATIONS

Holtwood Bus Reactance Coils

	70,000-volt values		13,200-volt values	
	Reactance	Resistance	Reactance	Resistance
1 bus reactance coil...	21.5 ohm	0.35 ohm	1.037 ohm	0.017 ohm

Highlandtown Bus Reactance Coils.

	70,000-volt values		13,200-volt values	
	Reactance	Resistance	Reactance	Resistance
1 bus reactance coil...	30.8 ohm	0.381 ohm	1.49 ohm	0.0184 ohm

Holtwood-Baltimore—Transmission Lines

	70,000-volt values		13,200-volt values	
	Reactance	Resistance	Reactance	Resistance
1 transmission line...	13.1 ohm	12.1 ohm	0.6330 ohm	0.5850 ohm

INDIVIDUAL REACTANCE AND RESISTANCE OF TRANSFORMERS

Holtwood Transformers

Operating No.	Office number	Serial number	Kw. rating	Per cent impedance	Per cent reactance	Per cent resistance (at 50°C)	Reactance in ohms phase H. T. (at 25 cycl.)	Resistance in ohms phase H. T. (at 50° C.)
1	102.	598555.	7,500	4.03	3.82	1.25	25.0	8.20
2	103.	598554.	7,500	5.14	5.00	1.20	32.7	7.83
3	108.	298572.	10,000	4.98	4.90	0.99	24.0	4.85
4	109.	301699.	10,000	4.98	4.90	0.99	24.0	4.85
5	107.	278098.	10,000	4.98	4.90	0.99	24.0	4.85
6	105.	750832.	10,000	4.90	4.84	0.84	23.7	4.12
7	106.	750833.	10,000	3.57	3.52	0.72	17.3	3.52
8	110.	343227.	10,000	4.98	4.90	0.99	24.0	4.85
9	111.	1198081	12,500	5.08	5.03	0.77	19.6	3.02
10	.....	....	....	....	....	....	....	......
Highlandtown Substation Transformers.								
2	207.	360644.	12,500	5.32	5.23	0.95	15.1	2.74
3	201.	237663.	10,000	4.94	4.79	1.21	17.2	4.33
4	202.	237664.	10,000	4.94	4.79	1.21	17.2	4.33
5	203.	237662.	10,000	4.94	4.79	1.21	17.2	4.33
6	204.	237661.	10,000	4.94	4.79	1.21	17.2	4.33
7	205.	278093.	10,000	5.05	4.90	1.22	17.6	4.41
8	206.	324822.	10,000	5.05	4.90	1.22	17.6	4.41

REACTANCE AND RESISTANCE OF GENERATORS AND REACTANCE COILS AT HOLTWOOD

Holtwood Generators

Number	Kw.-rating	Reactance (at 25 cycles)				Resistance at (50°C.)		Field current amps.	Averages		
		Starting value		Final value					H. T. reactance		H. T. resistance
		L. T.	H. T.	L. T.	H. T.	L. T.	H. T.		Start	Final	
1	10,000	1.32 Ω	53.4 Ω	5.67 Ω	229 Ω	.0651 Ω	2.63 Ω	275			
2	10,000	1.32 "	53.4 "	5.67 "	229 "	.0651 "	2.63 "	275			
3	7,500	1.21 "	48.9 "	5.67 "	229 "	.1075 "	4.35 "	275			
4	10,000	0.84 "	33.9 "	4.53 "	183 "	.0649 "	2.62 "	275			
5	10,000	0.84 "	33.9 "	4.53 "	183 "	.0649 "	2.62 "	275			
6	12,000	1.48 "	59.8 "	4.78 "	193 "	.0651 "	2.63 "	300			
7	12,000	1.48 "	59.8 "	4.78 "	193 "	.0585 "	2.36 "	300			
8	12,000	1.29 "	52.3 "	5.60 "	227 "	.0675 "	2.72 "	450	49.4	208	2.82

Holtwood Reactance Coils

	L.T. ohms	H.T. ohms	L.T. ohms	H.T ohms		
1	0 670 Ω	27.1 Ω	0 01479 Ω	0 598 Ω		
2	0.520 "	21.0 "	0.01082 "	0 437 "		
3	0.520 "	21.0 "	0.01082 "	0.437 "		
4	0.520 "	21.0 "	0.01082 "	0.437 "		
5	0.525 "	21.2 "	0 01432 "	0 579 "		
6	0 580 "	23.5 "	0 01582 "	0.640 "		
7	0.833 "	33.7 "	0.01495 "	0 604 "		
8	0.580 "	23.5 "	0.01495 "	0 604 "		
9	0.465 "	18.8 "	0.01405 "	0 570 "	23.4	0 545

From Public Service Electric Company,
Mr. N. A. Carle, Chief Engineer.

We distribute current at 13,200 volts, three-phase, 60 cycles, with the neutral not grounded. Several years ago, we contemplated grounding the neutral but decided at that time to install an arcing ground suppressor on the system. Since the arcing ground suppressor has been installed we have found that whenever a ground occurred, the surge suppressor would immediately make a dead ground on the phase that was in trouble and this would give the operator time to parallel another line or cable to take the bad one out of service.

The surge suppressor has never failed to operate in case the system became grounded on any one phase, and has, in several instances, in addition to protecting the system, saved employees from becoming electrocuted when they came in contact with the 13,200-volt wires.

We have found in many instances, that a line insulator may arc over, causing an instantaneous ground which is instantly stopped by the arcing ground suppressor cutting in. After taking out the suppressor and testing the line, we found in these cases that the ground had disappeared.

If a ground occurs on a 13,200-volt line paralleling a neighboring telephone wire, it causes a very slight disturbance, the extent of which depends upon the length of the paralleling circuits; the amount of current flowing, etc. In case a short circuit and ground occurs at the same time, the ground suppressor going in would cause very serious telephone disturbances, depending upon the length of the paralleling circuits. In order to remedy any trouble that might arise from this source, we installed in the operating station in which the ground suppressor is installed, instantaneous circuit-opening relays on each generator, so that in case a short circuit occurs on any feeder, the arcing ground suppressor cannot operate.

In my opinion it does not pay to ground the neutral of a transmission system unless the voltage is moderately high, say for aerial systems above 60,000 volts, and for cable systems, above 22,000 volts. It is not so very difficult to insulate cables for 22,000 volts, and it is not particularly hard to get line insulation that will stand up satisfactorily under 60,000 volts. The highest voltage under which we are operating at the present time is 13,200 volts.

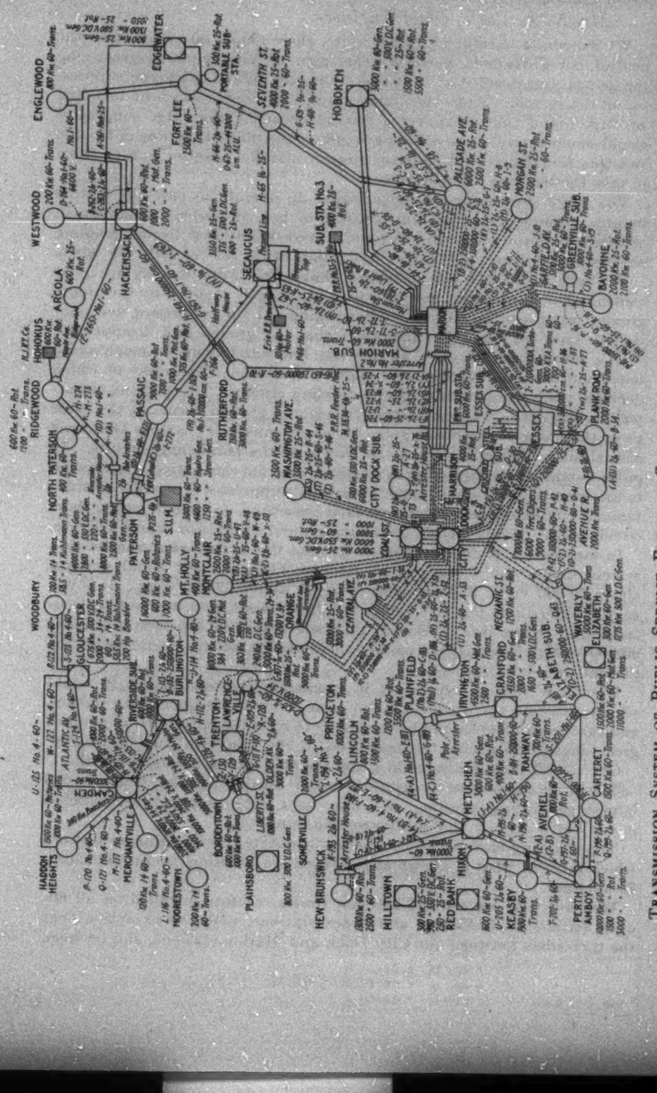
We have had no experience in grounding the neutral but it would seem to me that the proper place to ground it is in the generating station, and that resistances should be used so as to limit the current to an amount great enough to insure the operation of the relays in case of trouble

Our 13,200-volt transmission system in this state is shown herewith.

The surge suppressor is installed in our Marion Station, which is our largest generating station. We also have surge suppressors installed in our Perth Amboy and Burlington stations.

The charging current for the feeders connected to our Marion station, which takes in what is known as the Northern Division, is approximately 75 amperes.

We have five per cent 13,200-volt feeder reactors installed on all 60-cycle feeders from Marion and Essex stations, with the exception that the tie feeders between our City Dock and Marion stations, and between


EDGEWATER
ENGLEWOOD
FORT LEE
PORTABLE SUB-STA.
SEVENTH ST.
HOBOKEN
WESTWOOD
HACKENSACK
ARCOLA
SECAUCUS
SUB. STA. No. 3
PALISADE AVE.
MORGAN ST.
GARFIELD AV.
GREENVILLE SUB.
BAYONNE
HOHOKUS
RIDGEWOOD
MARION SUB.
MARION
PASSAIC
RUTHERFORD
NORTH PATERSON
PATERSON
S.U.M.
WASHINGTON AVE.
CITY DOCK SUB.
HARRISON
PRR SUB. STA.
ESSEX SUB.
ESSEX
PLANK ROAD
COAL ST.
CITY DOCK
AVENUE R.
WOODBURY
GLOUCESTER
MT. HOLLY
MONTCLAIR
CENTRAL AVE.
MECHANIC ST.
WAVERLY
ELIZABETH
ORANGE
PLAINFIELD
IRVINGTON
CRANFORD
ELIZABETH SUB.
ATLANTIC AV.
RIVERSIDE SUB.
BURLINGTON
LAWRENCEVILLE
TRENTON
PRINCETON
LINCOLN
RAHWAY
CARTERET
CAMDEN
MERCHANTVILLE
BORDENTOWN
LIBERTY ST.
OLDEN AV.
SOMERVILLE
METUCHEN
AVENEL
HADDON HEIGHTS
MOORESTOWN
PLAINSBORO
NEW BRUNSWICK
MILLTOWN
NIXON
RED BANK
KEASBY
PERTH AMBOY

TRANSMISSION SYSTEM OF PUBLIC SERVICE ELECTRIC COMPANY WITH PEAK LOADS FOR WINTER OF 1914-1915.

our Essex and Marion stations, have 2.5 per cent feeder reactances at each end, making a total of 5 per cent between the generating stations.

Between our City Dock and Marion stations, we have seven three-conductor 13,200-volt tie feeders. At each end of these feeders we have a seven-section selective relay which cuts out the bad cables in case any trouble occurs between these two stations. On all other feeders we use standard makes of circuit-closing inverse-time-limit relays.

When a ground or short circuit occurs on a cable or aerial line, a test is made for location as soon as possible. If the ground or short circuit is of such high resistance that a good test cannot be made, the resistance of the fault is decreased either by further breakdown from testing transformer, or by reduction with 600-volt direct current. The location is then made by means of a slide-wire bridge using the loop method. The chief causes are mechanical injury to the cable, defective joints, water in the cable (probably caused by a previous breakdown somewhere near this same location) and high-voltage disturbances, cause unknown.

From Pacific Light and Power Corporation,
Mr. H. A. Barre, Elec. and Mech. Engineer.

The arrangement of the high-tension distribution has been such that it has been possible to operate alternately with the grounded neutral system and the ungrounded delta system. The experience with the ungrounded delta system has been so disagreeable that we have made up our minds that under our conditions a grounded neutral system is essential.

The determining conditions seem to be the number of miles of line and the capacity of apparatus connected to the system.

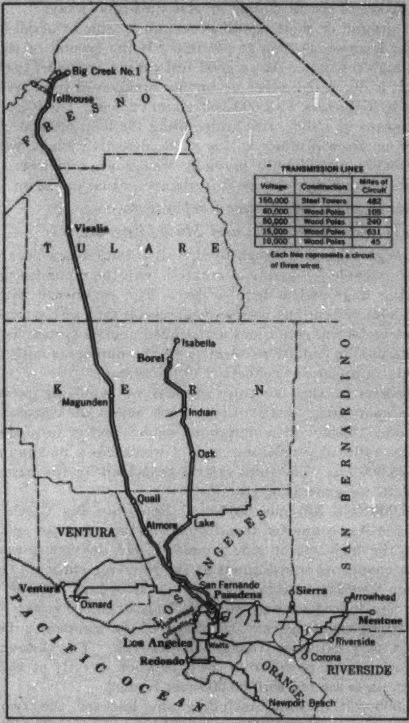
The business of this company consists of supplying power to the company's commercial distribution, which covers all classes of load and includes some 15,000-volt underground cable; and of furnishing service to two large railroad companies, each of which has a maximum demand of about 25,000 kw. The total system peak load for the past year was 76,000 kw. at the generating stations.

The 150,000-volt, 240-mile (386-km.) line from Big Creek is served through delta-star connected transformers at the generator end, with the neutral of the high-tension side grounded, and delivers power through delta-delta connected transformers at the receiving station. One-half of these latter lowering transformers have a secondary voltage of 15,000 volts. The remainder have a secondary voltage of 60,000 volts. The reason for this arrangement is that the base of the company's distributing system is a very extensive 15,000-volt network. The close-in parts of this net work receive power from the substation directly at 15,000 volts. The remote parts are fed with 60,000-volt feeders.

The 15,000-volt network, including the lines of the two railroad companies, embrace about 1600 miles (2574 km.) of line. The 60,000-volt system at the present time has about 85 miles (136 km.) of line.

Connected to the 60,000-volt system through compensators are about 300 miles (482 km.) of 50,000-volt line. Fed from this line are about 45 miles (72 km.) of 10,000-volt lines, and 45 miles (72 km.) of 15,000-volt lines, which are not otherwise connected to the net work. These 10,000-volt and 15,000-volt lines were not connected during the time of trouble with the ungrounded delta system which is described later.

On account of the fact that it was desirable to make the lowering transformers of the Big Creek system of the same design for both voltages so that they could be connected in series for 60,000 volts or in parallel for 15,000 volts, the 60-kv. and 15-kv. systems are in phase, hence they require delta-delta transformations at the remote points where the 60,000-volt feeders deliver to the 15,000-volt network. This precluded the possibility of a grounded star connection at the latter points of transformation.


Big Creek No.1
Tollhouse
FRESNO
Visalia
TULARE
Isabella
Borel
KERN
Magunden
Indian
Oak
Quail
Atmore
Lake
VENTURA
LOS ANGELES
SAN BERNARDINO
San Fernando
Pasadena
Sierra
Arrowhead
Mentone
Ventura
Oxnard
Los Angeles
Watts
Riverside
Corona
Redondo
RIVERSIDE
ORANGE
Newport Beach
PACIFIC OCEAN

TRANSMISSION LINES

Voltage	Construction	Miles of Circuit
150,000	Steel Towers	482
60,000	Wood Poles	108
50,000	Wood Poles	240
15,000	Wood Poles	631
10,000	Wood Poles	45

Each line represents a circuit of three wires.

TRANSMISSION LINES OF PACIFIC LIGHT AND POWER CORPORATION

Previous to the advent of Big Creek, the 15,000-volt system had been fed from a 40,000-kw. steam turbine plant of which the neutral was grounded. After Big Creek commenced service, this steam plant was needed only in emergencies and over peaks and the opportunity for establishing the ground through it was lost except during such hours as it might be operated. This left the 15,000-volt network without an established neutral, and it was found that whenever any trouble occurred which involved the accidental grounding of a 15,000-volt wire, the flow of charging current was sufficient to set up very serious surges in the system. These invariably caused breakdowns at more than one point on the system, sometimes three or four points, and the damage to the service and apparatus became a matter of most serious concern. These breakdowns were usually flash-overs or punctures of line insulators or bushings of transformers or switches.

It happened that while this condition existed, a new station was being built at Vernon, in which was being installed, amongst other things, a bank of three 5000-kw. transformers with a voltage ratio from 60,000 to 15,000. As an experiment, the 15,000-volt side of this bank of transformers was connected in star with the neutral point grounded, and the bank connected to the 15,000-volt bus bars. The 60,000-volt side was delta connected, and being, therefore, out of phase with the 60,000-volt bus, was left idle; in other words, an idle bank of transformers having closed-delta secondary was used to establish the grounded neutral on the 15,000-volt system. This bank had a very large capacity, full load being something like 600 amperes.

It was found that this effectively eliminated the surges and that after its installation whenever line trouble occurred the effects were localized in the section affected, and in practically every case the system of operation employed to sectionalize the net work, both automatically and manually, has served to protect the service. Some troubles have occurred on the 60,000-volt system, but since there is a ground established to it by connections to another plant, they do not at the present time appear serious.

This is largely due to the fact that the 60-kv. system is of comparatively small extent and when it grows, a system of connections to establish a grounded neutral of large current carrying capacity will be necessary.

From the foregoing experiences, our conclusions have been that under our conditions on a large system, the power stations should always be operated with a grounded neutral connection on the line side of the transformers. The generator side should be delta connected. At the receiving stations and distributing substations the delta-delta system is preferable.

We have not found the installation of resistance in the neutral of any advantage. The difficulty of making a good ground answers the resistance question.

On the 150,000-volt Big Creek lines, accidental grounds are handled as follows:

When the operator at the power house sees the recording ground ammeter showing a ground, he reduces the generator field by cutting in a special rheostat installed for this purpose. As soon as the ground ammeter drops back to zero he cuts out the resistance and the voltage comes back to normal, and the automatic voltage regulator takes control. This resistance is not cut out all at once, but the time which elapses from the time the arc breaks until normal voltage is restored, is from five to ten seconds.

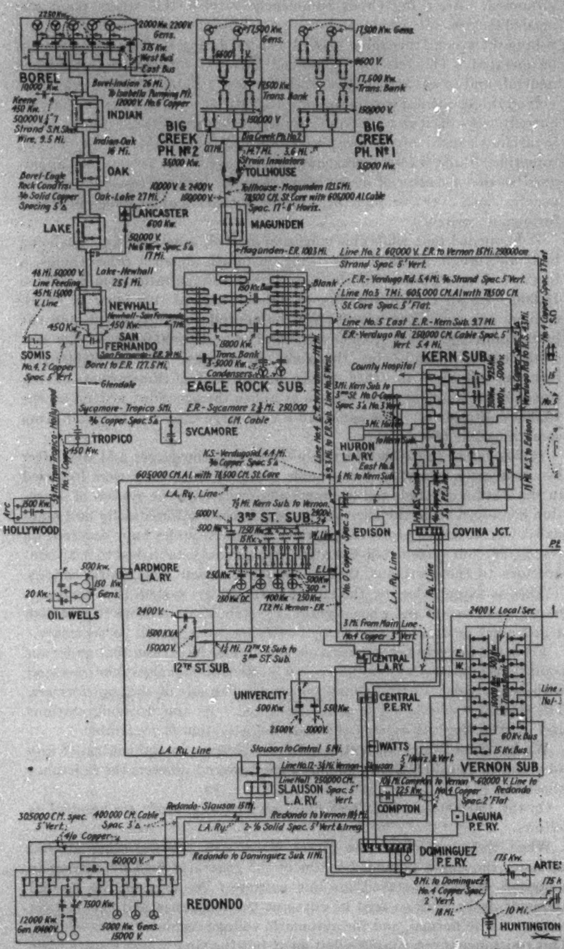
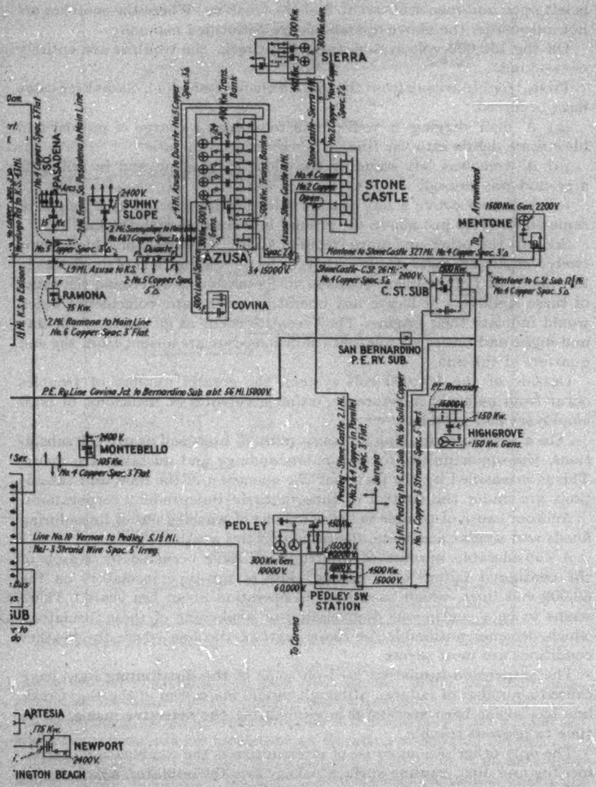

2250 Kw.
2000 Kw. 2200 V. Gens.
375 Kw.
West Bus
East Bus
BOREL
10000 Kw.
Borel-Indian 26 Mi.
To Isabella Pumping Pl.
12000 V. No. 6 Copper
Keene
450 Kw.
50000 V.
Strand S.M. Steel Wire, 9.5 Mi.
INDIAN
Indian-Oak 16 Mi.
OAK
Borel-Eagle Rock Cond'rs: ⅝ Solid Copper Spacing 5' △
Oak-Lake 27 Mi.
LANCASTER
600 Kw.
LAKE
50,000 V. No. 6 Wire Spac. 5' △ 17 Mi.
48 Mi. 50,000 V. Line Feeding
45 Mi. 15000 V. Line
Lake-Newhall 25½ Mi.
NEWHALL
Newhall-San Fernando 7 Mi.
450 Kw.
450 Kw.
SAN FERNANDO
San Fernando-E.R. 24 Mi.
Borel to E.R. 127.5 Mi.
SOMIS
No. 4, 2 Copper Spac. 5' Vert.
Glendale
17,500 Kw. Gens.
6600 V.
17,500 Kw. Trans. Bank
150,000 V
BIG CREEK PH. No 2
35,000 Kw.
17,500 Kw. Gens.
6600 V.
17,500 Kw. Trans. Bank
150,000 V.
BIG CREEK PH. No 1
35,000 Kw.
Big Creek Ph. No 2
0.7 Mi.
14.7 Mi.
3.6 Mi.
Strain Insulators
TOLLHOUSE
10000 V. & 2400 V.
150,000 V.
Tollhouse-Magunden 121.5 Mi.
78,500 C.M. St. Core with 605,000 Al. Cable
Spac. 17'-6" Horiz.
MAGUNDEN
Magunden-E.R. 100.3 Mi.
Line No. 2 60,000 V. E.R. to Vernon 15 Mi. 250,000 cm Strand Spac. 5' Vert.
E.R.-Verdugo Rd. 5.4 Mi. ⅝ Strand Spac. 5' Vert.
Line No. 3 7 Mi. 605,000 C.M. Al with 78,500 C.M. St. Core Spac. 5' Flat.
Line No. 5 East E.R.-Kern Sub. 9.7 Mi.
E.R.-Verdugo Rd. 250,000 C.M. Cable Spac. 5' Vert. 5.4 Mi.
150 Kv. Bus
Blank
15000 Kw. Trans. Bank
3-5000 Kw. Condensers
EAGLE ROCK SUB.
Sycamore-Tropico 5 Mi. ⅝ Copper Spac. 5' △
E.R.-Sycamore 2½ Mi. 250,000 C.M. Cable
SYCAMORE
TROPICO
450 Kw.
3½ Mi. from Tropico-Hollywood No. 4 Copper
Line No. 4 E.R. to Vernon
9.3 Mi. to E.R. Sub. Line No. 5 West
K.S.-Verdugo Rd. 4.4 Mi. ⅝ Copper Spac. 5' △
605,000 C.M. Al. with 78,500 C.M. St. Core
County Hospital
KERN SUB
3 Mi. Kern Sub. to 3rd St. No. 0 Copper Spac. 3' △ No. 3 West
3 Mi. Huron to Kern Sub.
HURON L.A. RY.
East No. 4
½ Mi. to Kern Sub.
11 Mi. K.S. to Edison
No. 4 Copper Spac. 3' Flat
Verdugo Rd. to K.S. 4.3 Mi.
COVINA JCT.
L.A. Ry. Line
1½ Mi. Kern Sub. to Vernon.
5000 V.
900 Kw.
3rd ST. SUB.
2400 V.
1250 Kw.
15 Kv.
W. Line
E. Line
EDISON
250 Kw.
250 Kw. DC
400 Kw.
250 Kw.
500 Kw.
300
17.2 Mi. Vernon-E.R.
No. 0 Copper Spac. 3' Vert.
L.A. Ry. Line
P.E. Ry. Line
1500 Kw.
Arc
HOLLYWOOD
ARDMORE L.A. RY.
500 kw.
150 Kw. Gens.
20 Kw.
OIL WELLS
2400 V.
1500 KVA.
15000 V.
1½ Mi. 12th St. Sub. to 3rd ST. Sub.
12th ST. SUB.
3 Mi. From Main Line
No. 4 Copper 3' Vert.
CENTRAL L.A. RY.
UNIVERCITY
500 Kw.
550 Kw.
2500 V.
5000 V.
CENTRAL P.E. RY.
WATTS
5' Horiz. & Vert.
2400 V. Local Ser.
E.
W.
60 Kv. Bus
15 Kv. Bus
VERNON SUB
Line No. 1
L.A. Ry. Line
Slauson to Central 5 Mi.
Line No. 12-3½ Mi. Vernon-Slauson
Line No. 11 250,000 C.M. Spac. 5' Vert.
SLAUSON L.A. RY.
10½ Mi. Compton to Vernon
No. 4 Copper Spac. 2' Flat
60,000 V. Line to Redondo
225 Kw.
COMPTON
LAGUNA P.E. RY.
305,000 C.M. spac. 3' Vert.
400,000 C.M. Cable Spac. 3' △
Redondo-Slauson 15 Mi.
Redondo to Vernon 18½ Mi.
4/0 Copper
L.A. Ry.
2-⅝ Solid Spac. 5' Vert. & Irreg.
60000 V.
Redondo to Dominguez Sub. 11 Mi.
DOMINGUEZ P.E. RY.
175 Kw.
ARTE
175 K
8 Mi. to Dominguez No. 4 Copper Spac. 2' Vert.
18 Mi.
10 Mi.
HUNTINGTON
7500 Kw.
12000 Kw. Gen. 10400 V.
5000 Kw. Gens. 15000 V.
REDONDO

Diagram showing the Distribution System


SIERRA
500 Kw.
300 Kw. Gen.
400 Kw.
Stone Castle–Sierra 4 Mi.
No. 2 Copper No. 4 Copper Spac. 2'Δ
SO. PASADENA
Arcs
15 Kw.
No. 4 Copper Spac. 3' Flat
Verdugo Rd. to K.S. 4.3 Mi.
2 Mi. from So. Pasadena to Main Line
No. 5 Copper Spac. 3'Δ
SUNNY SLOPE
2400 V.
2 Mi. Sunnyslope to Main Line
No. 6 & 7 Copper Spac. 3'Δ
Duarte
4 Mi. Azusa to Duarte No. 5 Copper Spac. 3'Δ
400 Kw. Trans. Bank
500 Kw. Trans. Banks
500 Kw. 500 V. Gens.
AZUSA
500 V. Local Service
Spac. 7'Δ
3ϕ 15000 V.
Azusa–Stone Castle 18 Mi.
1.9 Mi. Azusa to K.S.
2-No. 5 Copper Spac. 5'Δ
11 Mi. K.S. to Edison
RAMONA
75 Kw.
2 Mi. Ramona to Main Line
No. 6 Copper Spac. 3' Flat
COVINA
No. 4 Copper
No. 2 Copper
Open
STONE CASTLE
To Arrowhead
MENTONE
1600 Kw. Gen. 2200 V.
Mentone to Stone Castle 32.7 Mi. No. 4 Copper Spac. 3'Δ
Stone Castle–C. St. 26 Mi.
No. 4 Copper Spac. 3'Δ
2400 V.
1500 Kw.
C. ST. SUB
Mentone to C. St. Sub. 12⅝ Mi.
No. 4 Copper Spac. 5'Δ
SAN BERNARDINO
P. E. RY. SUB.
P.E. Ry. Line Covina Jct. to Bernardino Sub. abt. 56 Mi. 15000 V.
P.E. Riverside
15000 V.
150 Kw.
HIGHGROVE
150 Kw. Gens.
2400 V.
MONTEBELLO
105 Kw.
No. 4 Copper Spac. 3' Flat
Pedley–Stone Castle 21 Mi.
No. 2 & 4 Copper in Parallel
Spac. 3' Flat.
Jurupa
22⅝ Mi. Pedley to C. St. Sub. No. 1/0 Solid Copper
No. 1-Copper 3 Strand Spac. 5' Vert.
PEDLEY
450 Kw.
Line No. 10 Vernon to Pedley 5.1⅝ Mi.
No. 1-3 Strand Wire Spac. 5' Irreg.
300 Kw. Gen. 10000 V.
15000 V.
60000 V.
4500 Kw. 15000 V.
60,000 V.
PEDLEY SW. STATION
To Corona
SUB
ARTESIA
175 Kw.
NEWPORT
2400 V.
INGTON BEACH

OF THE PACIFIC LIGHT AND POWER CORPORATION

At the receiving station at Eagle Rock the operator kills the field of condensers at once by opening the circuit of the automatic voltage regulator. As soon as he sees that the power house has overcome the trouble and the voltage is coming up again, he closes the regulator circuit.

Governors at the power house must take care of the speed when the load is dropped. They always do this.

For the remainder of the system on those lines which are controlled by automatic circuit breakers, the switches are closed after opening on trouble, and if the short circuit or ground is still on the line, the switch is left open and men sent out to find the trouble. Where the switches are not automatic, the above operations are performed manually.

On the 150,000-volt system from Big Creek, the troubles are entirely of two kinds:

First, trouble arising from the human element of which class three cases have occurred.

(a) A man digging a well put in too heavy a charge of powder and blew some debris into the line.

(b) A tree was left standing too close to the line and in felling it a ground was caused.

(c) A farmer drove a hay stacker with derrick erected at a height of some 36 ft. (10.9 m.) above the ground into contact with the line.

Second, the other and more frequent cause of trouble, of which some twelve or fifteen cases occur each year, is the spilling over of insulators in the middle half of the line. We have not been able to determine the cause of these spillovers or locate any operating or climatic coincidents which would indicate their origin. They seem to occur at all hours of the day and night and under all weather conditions, but are absent from the end quarters of the line.

Outside of the 150,000-volt system, the greater number of troubles occur from personal interference, either accidental or malicious, of both employees and outsiders.

On a system containing so many miles of lines and nearly 100 substations, the opportunities for misunderstandings and mistakes are many. This is intensified by the fact that the operation of the lines and substations are under the control of three entirely independent corporations.

Another cause of trouble is the usual one of washing out of lines during floods and similar accidents, depending on the weather.

A considerable number of interruptions have occurred by reason of the continued failure of a certain class of pin-type insulators on the 50,000-volt lines, which have been in operation about ten years. There seems to be a continuous depreciation or weakening of these insulators, which becomes noticeable, in those parts of the line where the weather conditions are most severe.

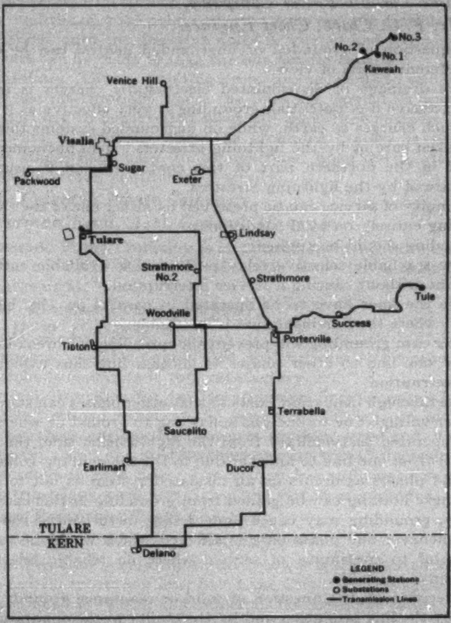
The suspension insulators used on some of the distributing lines have caused a number of failures, although careful inspection of the Big Creek line has so far been successful in eliminating the defective insulators in time to prevent trouble.

The only other serious cause of interruption is the combination of summer fog and dust, causing surface leakage over the insulator, which carries sufficient current to set the pole on fire. In the last few years, interruptions from this cause have been practically eliminated by the expedient of electrically connecting the insulator pins, which are of iron.

No complete detailed analysis of these various kinds of trouble has been made, so that I am not able to give you more than the above generalization.

From Mt. Whitney Power and Electric Company,
Mr. Fred G. Hamilton, Supt. W. Div.

This company is operating practically 200 miles of 33,000-volt transmission lines. The lines are arranged in the form of a figure eight and are fed by four hydroelectric and two steam plants.


No.3
No.2
No.1
Kaweah
Venice Hill
Visalia
Sugar
Packwood
Exeter
Tulare
Lindsay
Strathmore No.2
Strathmore
Tule
Woodville
Success
Porterville
Tipton
Terrabella
Saucelito
Earlimart
Ducor
TULARE
KERN
Delano
LEGEND
● Generating Stations
○ Substations
—— Transmission Lines

Transmission Lines of Mt. Whitney Power and Electric Co.

The neutral is grounded on each hydroelectric plant, but there is no ground at the steam plants or any of the substations.

The elevation of the hydroelectric plants is practically 1150 ft. (350 m.) while the substations are located at an elevation of 350 ft. (106 m.)

It has always been our method of operation and we have no data upon non-grounded operation. We have experienced no particular difficulties particularly chargeable to the grounded system. We have had grounds and short circuits on the transmission line which we cleared up by cutting out the faulty section, by trial, between the substations. The switching is controlled by a load dispatcher at the Visalia steam plant.

This system gives us very efficient service and the worst cases of interruptions are only of short duration. Since our voltage is comparatively low and we have had no experience on non-grounded operation, we are not in a position to give comparative data, which would be of much assistance. For our voltage we feel that non-grounded lines would probably give us as good service as our grounded system.

From The Toronto Power Company,
Mr. F. G. Clark, Chief Engineer.

The question of grounded or ungrounded neutral can be considered from different points of view.

Where drainage of accumulated electrostatic charges is required to avoid excessive d-c. potential, grounding is very effective as it will drain off all such charges to earth, while on ungrounded systems this will have to be taken care of by the lightning arresters. This phenomenon is very unusual in the northern part of this continent, and is usually safely taken care of by the lightning arresters.

Continuity of service can be preserved by either one of the two systems depending entirely on local conditions.

Grounding should be applied:

Where a reliable selective relay protection is available cutting out a faulty line without causing a service interruption.

Where the lines have to be operated in parallel on the high-tension side and where the line insulation is unreliable.

In this case grounding will prevent the spreading of a breakdown on one phase of one line to other phases of another line thus avoiding a long total interruption.

Where this high insulation exists so that other phases can stand momentary over-voltage due to one phase flashing to ground or where the lines can be operated sectionalized from the high-tension side, the spreading of a fault from one line to another due to the momentary voltage rise on the sound phases as occurs on an insulated system, is not to be feared. Accordingly nothing can be gained from grounding in this case. On the contrary, grounding may cause unnecessary disturbances and interruptions, whenever one phase only is affected which would be particularly detrimental to continuity of service where no reliable selective relay protection is available.

The decision on the question of solid or resistance grounds should be guided by the line insulation and by the ability of the apparatus to withstand short-circuit strains. Where low and unreliable insulation on the line is the prime object of grounding and where the equipment is built to resist effectively any short-circuit strains, solid grounds should be used.

Where, however, the insulation is high and reliable and where the equipment may be somewhat mechanically weak, a ground resistance will be desirable to reduce the mechanical strain of single-phase short circuits.

I would further advise that our transmission system from Niagara Falls to Toronto is composed of four circuits operating ungrounded at 60,000 volts. The transformers on either end are delta connected.

From Puget Sound Traction, Light and Power Company,
Mr. G. E. Quiman, Engineer, Seattle Division.

The four hundred odd miles of high-tension transmission lines of this company are delta connected and operated without grounds.

It is our opinion that probably the chief advantage of grounding the neutral of a high-tension transmission system, is that it eliminates most of the trouble experienced on an isolated system from arcing grounds. The principal disadvantage of grounding is that line trouble more frequently results in interruptions to service. It is our experience that the insulating qualities of wood poles and cross arms make it possible to retain a line in service until the defective point is located and frequently until arrangements can be made to take the line out for repairs.

Even insulator failures resulting from arcing grounds seldom cause serious service interruptions where the lines are carried on wood poles.

We are inclined to believe that where all important business is served from duplicate transmission lines, the grounded system is preferable, but where single lines have to be depended upon the isolated system makes possible greater continuity of service.

From The Colorado Power Company,
Mr. Norman Read, Asst. General Manager.

The Colorado Power Company is at present operating both its 100-kv. transmission and 13-kv. distribution systems connected in delta and with no artificial neutral.

From The Montana Power Company,
Mr. H. H. Cochrane.

This company operates ungrounded, and believes this method preferable. Telephone operation is very satisfactory.

The typical protection for two transmission lines in parallel consists of three-pole overload relays at the generating station end of the line, operated by three current transformers in each line, and three-pole reverse-current relays operated by three current transformers and potential transformers in each line. The system has sufficient line charging current to trip relays when one wire of the system is grounded.

From Utah Power and Light Company,
Mr. Markham Cheever, Chief Engineer.

From our principal generating stations power is transmitted at 130,000 volts to a central substation near Salt Lake City. At this substation the voltage is reduced to 44,000, and numerous feeders make connection with an extensive and complicated network of 44,000-volt lines. Everything is now operated with neutral ungrounded and we see no reason for changing the 130,000-volt system, since up to the present time there have been during two year's operation, practically no operating difficulties.

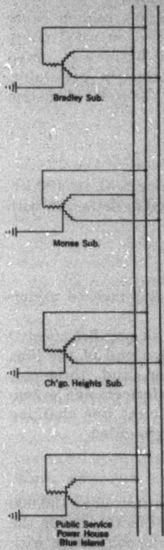
Upon the 44,000-volt system we are considering the installation of a suitable grounding compensator located at the main central substation for the purpose of facilitating automatic sectionalizing of disabled lines and for the reduction of high-voltage strains.

Our earlier experience in this territory with 44,000-volt systems of moderate sizes indicated the advisability of operating with neutral ungrounded, since there were many cases of grounds which would clear themselves without disturbing service and some cases of dead grounds which permitted the continuance of operation until repair could be made. During the winter of 1912 and 1913 a number of systems were paralleled and since that time many extensions have been made. With the enlarged system we are finding that practically all cases of grounds develop into serious trouble and it is often difficult to localize the disturbance.

From the Chicago and Interurban Traction Company,

Mr. Robert J. Bell, E. E.

We have a 33,000-volt three-phase 25-cycle transmission line, extending from the Public Service Co. power plant at Blue Island, to Bradley Ill., a distance of about 45 miles (13.7 km.) This line consists of three No. 4 hard drawn copper wires placed on 35-ft. (10.6-m.) cedar poles spaced 110 ft. (33.5 m.) apart.



BRADLEY SUB-STATION TRANSFORMERS 1950-430 VOLTS. POWER HOUSE TRANSFORMERS 9000 -33000 VOLTS

We have three substations on this line with one 500-kw. synchronous converter in each of these stations. The Bradley substation has, in addition to the converter, a 500-kw. frequency changer, 25 cycles to 60 cycles.

Our transformers are Y-connected on the primary in all the substations. At the power plant they are Y-connected on the secondary side.

We have a telephone line on the same poles, but do not experience any serious trouble. There is some noise but not enough to interfere with service. This line is transposed at every fifth pole. The neutral connection at the transformers is grounded, and we have not experienced any trouble therefrom. We have experienced one great advantage by grounding the neutral, that is, in case of line trouble, where one of the phase wires becomes grounded, we are able to test out and find what phase it is, then have the disconnecting switches pulled out on this phase at each end. We are then able to operate on the remaining two wires by the use of the grounded neutral.

This system has saved us a great number of hours of shut-downs and we have had no trouble caused by this system of operation.

As to the advisability of grounding the neutral, while it may not work successfully on all systems, I think it worth while to try it out, especially if the transformers are not loaded too heavy.

We operate grounded at the substations and at the power plant.

We lost some insulators during electrical storms (which having the neutral grounded may encourage). All our trouble has been from direct lightning strokes, It makes our telephone line a little noisier when we are working on two line wires than otherwise.

A general layout of the line with the transformer connections is shown herewith. We have an overload relay on our oil switch which is set to trip out on normal overload, and we make use of the current to ground when we are using two line wires.

These grounds are cleared by linemen sent over the circuit. The causes are various, but very frequently can be traced to a broken insulator. I think no current flows to ground through the ground connection but have never made any test to that effect.

From Alabama Power Company,

Mr. W. E. Mitchell, Operating Manager.

Our experience here in Alabama has caused us to become firm advocates of the grounded neutral on our high-tension system, and grounded solidly without any resistance whatever. This is based on about nine months of operation with it ungrounded and a year's operation with it grounded. This matter is discussed somewhat briefly by Mr. Dewey and myself in a paper which we read before the S. E. Section of the N.E.L. A. in September of this year. We found that our insulator troubles in the way of breakdowns and flash overs were much worse and much harder to locate and control when ungrounded than when grounded. Grounded neutrals also made it possible to use the selective relays for cutting out immediately any section of line which might be in trouble. The grounding of the neutral turns any arcing ground immediately into a phase-to-neutral short circuit, which is much simpler to handle and to relay for than an arcing ground on an ungrounded system.

From The J. G. White Engineering Corporation,

Mr. C. D. Gray, Asst. Electrical Engineer.

My personal opinion is that systems up to about 38,000 volts should be operated with isolated-delta connections, although this depends upon the local conditions under which the system under discussion might be connected. For systems above 38,000 volts I believe the star connection with grounded neutral to be the best, although in this case also the local conditions would influence a decision as to whether it should be star or delta. The locality in which the line is to be operated I believe has a great deal to do with it, and also the chances of interference with telephone, telegraph and other systems of this kind.

Our experience has been that the delta system has less influence on telephone and signal circuits than the grounded-neutral connected system. A great disadvantage of the star-connected grounded-neutral system is the fact that the circuit breakers are thrown out on trouble on any one of the three wires of the system, and that it is practically impossible to operate with one wire down, or with one transformer out of service in a bank of three, unless the conditions of grounding are very favorable, where as with the delta system the open delta-connections of transformers can be used temporarily at least without causing a great deal of trouble.

Another point in favor of the star-connected grounded-neutral system is the fact that trouble on the line can be located better by means of the Nicholson or other similar testing method. The line insulation has been so improved in the last few years that it is now possible to operate delta connected whereas previously it was not possible on account of the insulators, it being necessary to reduce the potential to ground in order to favor the insulators.

With regard to the operation of three-phase systems, I agree very well with the paper of Messrs. Jollyman, Downing and Baum, given before the Institute on May 29, 1914. This would be especially true with any system operated with pin-type insulators similar to that of the Pacific Gas and Electric Co's. system.

In conclusion I would say that I am not greatly in favor of one system over the other, but that the local conditions would largely influence a decision in the matter, and it seems to me that it is more a matter of experience from operation in any particular section of the country rather than the result of theoretical decision.

From Pacific Gas and Electric Company,

Mr. J. P. Jollyman, Engineer Electrical Construction.

The experience of the Pacific Gas and Electric Company with the grounded neutral has been covered in considerable detail in the paper by Messrs. Jollyman, Downing and Baum, presented to the Institute in 1914 (TRANSACTIONS A.I.E.E., Vol. XXXIII, pp. 767). Our further experience with this system has confirmed the opinions expressed at that time.

From Mr. Charles E. Waddell,

Consulting Electrical Engineer.

The two high-tension systems with which I am most familiar do not ground the high-tension neutrals: these systems are the North Carolina Electric Power Company, which serves Western North Carolina and which operates at 66,000 volts and 6600 volts, and the Florida Power Company which serves the west coast of Florida in the mining district and which operates at 60,000 volts.

My inclination, which is tending toward a fixed opinion, is that it is possibly wise to ground the secondary system of small substations supplying consumers regardless of the secondary voltage, be it even as high as 2000, the object being the protection of life and property. On the other hand I am forced to conclude,—certainly for this vicinity,—the grounding of the neutral of high-tension transformers at the tie-in substations would be a menace rather than a protection. As you are fully aware, the recent general practise is to ground the secondaries of the instrument transformers used in connection with the switchboards. While this has proved a great protection as far as life is concerned, I have found that the practise has increased the number of burnouts and really interferes with continuous service.

A considerable number of additional replies were received which contained no information of special interest.

An examination of the above replies emphasizes what is perhaps the proper point of view on this subject, namely, the effect of grounding the neutral of a high-tension system will be different in different sorts of systems, it may be an advantage in some and a disadvantage in others. Furthermore the effect of grounding through a resistance is different from the effects of grounding directly. Each case must be considered on its merits and most of the probable cases are illustrated by the above replies.

The neutral may be grounded in different plants for various reasons:

(a) To prevent throwing full line potential on other line wires by a ground on one line.

(b) To enable relays to operate quickly and surely or selectively.

(c) To prevent arcing grounds.

(d) To locate breakdowns.

(e) To take the place of one line wire on a three-phase system when this wire may be interrupted. This requires the disconnection of the grounded wire.

(f) To enable grounds to be extinguished by the Nicholson automatic system of grounding through a fuse.

When the ground connection is specifically omitted it is usually to enable operation with one line grounded and thus minimize interruptions.

Actual practise shows that grounding is more often resorted to on high voltage, and in large and complicated systems. Wooden-pole, wooden-crossarm lines below 60,000 volts offer the best chance of operating successfully with one line grounded.

In conclusion attention is called to the very full and illuminating reports of several of the companies sending replies. The thanks of the committee is due to these and the others who have cooperated with the committee in collecting the data reported.

DISCUSSION ON "REPORT OF TRANSMISSION COMMITTEE," CLEVELAND, OHIO, JUNE 27, 1916.

N. A. Carle: I think that in general it is recognized that higher temperatures occur in transformers, motors and generators at altitudes above 600 feet than for the same loads at sea level. At the present time, I understand, the Standards Committee of the Institute is trying to determine a suitable corrective factor or formula to meet this condition.

M. O. Troy: Mr. Carle has correctly summarized the matter when he says that correction for altitude is one of small magnitude.

Operating men, who in the past have bought electrical apparatus with reasonable margins of safety, in all probability have not noticed any effect of altitude, and for that reason so state in their reports. If, however, they had measured their loads and capacities carefully and compared the heating values so obtained with those obtained by the manufacturers—in all probability at lower altitude—they would have found a difference.

In the standardization work of the Institute, we have tried to establish safe but definite temperature limits of operation.

I think there is no doubt that modern apparatus working at sea level to the limits prescribed by the Institute will exceed those limits if the apparatus is operated at the high altitudes under discussion; and if the sea-level temperatures represented a maximum for the safe operation of certain classes of insulation, the temperatures at the high altitudes would go beyond safe allowable limits.

Correction factors, therefore, should be recognized and definitely established by the Standards Committee as soon as reliable data are available.

Peter Junkersfeld: Our experience in Chicago with the grounded neutral covers the past fifteen years. The first experience was the initial installation of the four-wire three-phase system of primary distribution operating at 2300/4000 volts, 60 cycles. This system was extended so rapidly that in a few years it absorbed all of the older single-phase generating stations, and has since been the standard arrangement in the Chicago territory.

Within a year after our initial experience on the 60-cycle system the voltage on the 25-cycle system was raised to 9000 volts and the neutral grounded, which has since then been standard practise on that system.

Both of these systems have grown so rapidly that the experience in Chicago with grounded neutrals has been quite extensive during the past fifteen years as may be illustrated to some extent by the mileage of cable or conductor operated with grounded neutral, which at this date is as follows:

9000-volt,	25-cycles,	3-phase	cables	undg.	485 miles	(781 km.)
20000 "	25- "	3- "	"	"	83 "	(132 km.)
12000 "	60- "	3- "	"	"	158 "	(254 km.)
					726	

2300/4000-volt, 60-cycle single conductor equivalent underground 1518 (2444 km).

2300/4000-volt, 60-cycle single conductor equivalent overhead 7850 (12638 km.)

The reason for stating the last two in conductor miles is that there are a considerable number of single-phase branches connected to the three-phase four-wire circuits. In such cases and also on some other circuits single-conductor instead of three-conductor cable is used.

The 25-cycle 9000-volt system is supplied by turbo-generators ranged in capacity from 12,000 to 30,000 kw. This system is divided into sections, so that the generator capacity connected to the largest section does not exceed 80,000 kw. Three of these sections are interconnected by tie lines with protective reactance coils, while the fourth section is connected to the system by means of underground tie lines about 8.3 miles (13.4 km.) long without reactance coils. Our standard practise is to have the neutral grounded on one turbo-generator of each of the four sections. The neutrals are grounded through iron-grid rheostats having a resistance of 2½ ohms. One of these rheostats is provided for each system section, and is connected between ground and a neutral bus, which can be connected by means of an oil circuit breaker to the neutral of any turbo-generator on that system section.

The neutrals of the 12,000-volt 60-cycle turbo-generators are grounded in a similar manner through iron-grid rheostats having a resistance of three ohms.

The energy for the 2000-volt 25-cycle system is supplied by means of three 5000-kw. three-phase transformers stepping up from 9000 to 20,000 volts. The primary is delta and the secondary is star connected with the neutral of all three transformers grounded solid.

The 2300/4000-volt 60-cycle system is supplied by 25- to 60-cycle frequency changers and 1200-volt to 4000-volt three-phase transformers. The transformers are delta on the primary and star connected on the secondary. The neutrals of the 60-cycle generators and of the frequency changers are all connected solid to ground, and the same is true of the neutrals of all of the transformer secondaries.

The experience with grounded neutral on the above systems has been very satisfactory, the principal benefits having been the following:

1. It insures the prompt automatic disconnection of any faulty feeder.

2. It prevents the existence of delta voltage to ground on

other lines and apparatus in case of a ground on any part of the system.

3. It helps in locating breakdowns of lines and of apparatus.

4. It prevents arcing grounds and therefore voltage disturbances.

It must be noted that the last statement refers to specific conditions. Under some conditions differing from these it may not always be advisable to ground the neutral. I with several other engineers made a rather extensive inquiry a few years ago as to the advisability of grounding the neutral on 33,000-volt overhead lines connecting cities and towns in Illinios. In this case it was decided to install a delta connected system without grounded neutrals, except in such few special cases as might later prove to be advisable. The reasons for that decision were as follows:

1. The general secondary distribution system was four-wire 2300/4000 volts. As this necessitated a star connected secondary on the step-down transformer, acknowledged good practise determined a delta connected primary on these transformers.

2. On account of consolidations, it was necessary to operate in parallel a number of different properties, and because of phase relations it was found most advantageous to have the step-up transformers at the generating stations star connected on the primary and delta connected on the secondary.

3. The argument, that with an ungrounded neutral the system could be operated in emergencies with one phase wire grounded, had considerable weight.

The 33,000-volt lines have been built so rapidly during the four years since the decision referred to was made that they now aggregate 1000 miles (1600 km.) in Illinois alone. These lines are not all owned or operated by the same companies, but in this matter and in many other matters follow the same principal engineering standards.

I will repeat, that on the overhead system the experience is still too limited to draw absolutely final conclusions, but as far as the underground system is concerned, covering a period of fifteen years and the large mileage mentioned, we feel under those conditions that grounding of the neutral has proved a wise course.

E. E. F. Creighton: There are some cases where the neutral can be judiciously grounded, and there are other cases where it is better not to ground it, if the proper precautions are taken. The greatest objection to a non-grounded neutral at the present time is the arcing ground, and the result it gives on the system.

David B. Rushmore: In connection with the installation of the various transmission systems in this country, there has been a continual discussion regarding the relative merits of grounded Y and ungrounded delta transformer connections. As electrical apparatus, and especially lightning arresters, have developed the situaton has undergone different modifications, so that in some places one and at other times the other connection has seemed desirable.

Transmission systems have, as a rule become high-tension distributing systems, and the network of overhead wires has become greatly extended and the load situation much more complicated. The important question of operating so as to deliver continuous service has brought about the development of automatic relays, so that disturbances may be instantly localized. For this purpose the use of the grounded Y has many decided advantages and, in most cases, at the present time is to be recommended.

N. A. Carle: The preponderance of opinion seems to be against the grounded system. We in New Jersey have a lot of transmission lines there, and have an ungrounded system which is very satisfactory.

J. T. Lawson: The system mentioned by Mr. Carle operates at 60 cycles, 13,200 volts with an ungrounded neutral, and is equipped with an arcing ground suppressor.

Mr. Rushmore, if I understood him correctly, brought out the point of non-interruption to service on a grounded neutral system. With an ungrounded system equipped with an arcing ground suppressor, I think you come closer to this condition than without the use of the suppressor. Instead of having a cable open at both ends thus shutting off the service, with the arcing ground suppressor it is possible to leave the grounded cable in, parallel it with another cable, or take it out, with no interruptions to service.

The action of circuit-opening relays, possibly, with the grounded system may be more satisfactory, but with single-phase arcs to ground I do not see where fine relay adjustment is necessary if the arc is extinguished before it has a chance to develop into a short circuit.

David B. Rushmore: My remarks applied mainly to high-voltage systems, 100,000 volts and over.

John B. Taylor: The detailed experiences contributed on operation of three-phase transmission systems with, and also without, neutral grounded, are of interest and value. The committee's conclusion that for different cases, grounding "may be an advantage in some and a disadvantage in others",—is quite in agreement with previous discussions of the same question.

N. A. Carle: We have a balanced potential relay, and the unbalancing of one phase to ground puts that cable out of business, and we simply get it afterwards on tests, and another cable goes in.

John B. Taylor: You determine that unbalancing, I assume by an arrangement of potential transformers connected to your bus bars and also connected to ground, which means that your system is grounded,—you have a neutral ground on the system,—that neutral ground is made on relatively small potential transformers instead of on relatively large generators, but, technically, the system is grounded on account of the potential transformers connected in Y with their neutral grounded.

N. A. Carle: There is only one connected with the relay which makes an artificial ground through the oil switch.

P. H. Chase: I think I can explain that point. The grounded neutral system is so-called because the ground is of sufficiently low resistance that the current to ground operates a relay on the grounded phase. This is distinguished from the ungrounded neutral system with a suppressor, in that the three potential transformers which are connected in star with the neutral grounded allow only the exciting current of the potential transformers to flow to ground. Though there is this metallic connection to ground, the system with a suppressor cannot properly be classed as a grounded neutral system because the exciting current of the potential transformers is not of sufficient magnitude, and is not intended, to operate the overload relay on the grounded cable.

John B. Taylor: It seems finally to come to a definition of technicalities.

E. E. F. Creighton: If we add to Mr. Taylor's remarks some figures, it may help to straighten out the matter. The current to ground in potential transformers is a small fraction of an ampere. The current that reduces one phase of this system to ground is over sixty amperes. It would take more than forty amperes to reduce it to half potential to ground, and, therefore, I consider the system is non-grounded, even though the potential transformers are connected to ground at the neutral, because they could not in any way maintain the neutral at grounded potential.

H. R. Woodrow: Our experience has not shown that any advantage from surges has been gained by grounding the neutral of the system. The neutral of our sixty-cycle system was grounded more than two years ago and we have never been able to find any difference in surges before and after grounding. The 25-cycle system has never been grounded and we have never had any serious disturbance due to high-frequency surges.

In a case of some 15,000-volt cables, the failures looked rather suspicious of surges, and we therefore grounded the neutral of this system in an attempt to reduce the surges. The result which we have obtained in the last year and a half, since this system was grounded, shows scarcely any difference in the characteristics or number of failures.

In the ungrounded system we have the grounding relay protection with a grounding transformer, which will indicate a ground on any feeder, so that the defective feeder can be taken out of service before it develops into a short circuit.

Edmund C. Stone: The system I am familiar with is a system of about 175 miles of 11,000-volt transmission, three-phase. About fifty miles of that is underground. We find that nearly all of our troubles originate in the overhead system and set up arcs in the grounds which break down the cable system. I think where the system is entirely cable probably that trouble would be eliminated, but we have a great deal of trouble from arcing grounds originating in the overhead system, which set up voltage disturbances, and in turn break down the cable system. We have decided to adopt a grounded neutral on the theory that saving the cable is more important—the downtown system is all underground— than maintaining continuous service on the overhead system.

So far we have never had a case in five years where we have been able to operate the system with one phase of the overhead grounded. That seems to be the main recommendation for the three-phase system, and I would be interested to know if there are many examples on record where the three-phase system is actually operated and profitably operated, when one phase was temporarily grounded,—that is an arcing ground starts and creates such a disturbance that it puts us out of business until we have isolated the defective line.

Fred L. Hunt: I can tell you of a 66,000-volt three-phase circuit which within the last month operated three hours carrying a 4000-kw. load with one wire broken, the two ends of the broken wire being about 150 feet apart on the ground. The load was carried in this way until a steam plant could be pressed into service to relieve the line.

L. N. Crichton: Mr. Stone's remarks remind me of a case where the records of a transmission company covering a period of several years' operation were studied, and only two cases found where power was supplied with one wire on the ground, and even in these cases the service was finally interrupted before the ground was located. An interruption is not caused by the ground itself but by the disturbances which it creates, a single ground often causing several insulation failures at widely separated points on the system. The principal difficulty in the case of an undgrounded neutral system is that you can not locate an accidental ground, the only way of doing it on a system of any size being by cut and try methods, which with the telephone out of service is a difficult job, and the chances are good that before you get through with the process you will interrupt practically the entire system.

Now this applies only to large systems, say a 45,000-volt system, having 1,000 or possibly 1,500 miles of line. With a small system, no matter what the voltage may be, or with a simple system, say only two parallel lines, with a substation on one end and a generating station on the other end, the chances of operating with one wire grounded are very good. The reason why the large system suffers more than the small one is not because the voltage strains are greater but because there are more weak points which are liable to be damaged. As a rule, these weak points occur in apparatus rather than on the lines, therefore, the amount of apparatus connected to the system is of more importance than the number of miles of circuit. If the neutral is grounded the voltage strain will be reduced so that the disturbance will not cause such widespread damage and every ground will be promptly disconnected by the automatic circuit breakers.

R. F. Schuchardt: I suggest that Mr. Hunt tell us in connection with the case he cited, something as to the nature of the soil the wires fell on, whether it was in wet grass, or sandy soil, or what the character of the soil was.

Fred L. Hunt: It was in the Connecticut valley, in western Massachusetts, in sandy soil. The grass and brush in the vicinity were set on fire and we were notified of the trouble by a farmer who said his field was on fire. The wire fence around the field seemed to be charged and showed signs of heavy static discharges.

E. T. Street: We have operated 13,000-volt lines with one wire on the ground, supplying power to our substations until we were able to switch over to another line. It has been my observation when we have had lines on the ground—we have had two wires down within one foot or eighteen inches of the other on sandy soil—that the breakers would stay in. With the ungrounded system we can have wires down without causing any interruption to our system as a whole.

Harold Goodwin, Jr.: As to whether the New Jersey system is a grounded neutral system or not, it seems that the committee might do the members of the Institute a service by defining for future discussion whether we shall consider such a system as grounded or not.

W. A. Carter: We had a case where one wire came down on a 100,000-volt transmission line. We buy our power from the Colorado Power Company. The power station was about thirty-five miles away. With one wire carrying current through the ground at the broken span we were able to get several thousand kilowatts, which added to the load carried by our steam plant was sufficient to carry our evening peak load.

Bernard Price: The scheme with which I am connected is controlled by two power companies, viz., The Victoria Falls & Transvaal Power Co. Ltd., and the Rand Mines Power Supply Co., Ltd., the latter being a subsidiary of the former. For present purposes the transmission and distribution systems of the two concerns may be treated as one because they are inter-connected and are operated as one system. The district is at an altitude of nearly 6,000 feet above sea level and is prone to severe lightning storms during at least six months out of the twelve and the major portion of the system is overhead.

For a system of our type, it is unquestionably wise to earth the neutral. Instances have arisen where a certain portion of the system has become insulated from earth during a lightning storm and the result has always been a very large increase in the number of faults. Whilst I realize that each scheme should be dealt with on its merits, I find it most difficult to conceive any overhead network in a lightning district which would not benefit by an earthed neutral.

Our experience of running the system with the neutral grounded has been most satisfactory and has shown conclusively the advantages to be derived from such grounding on a system of the type in question. In the early stages of development of the scheme, the system was run with an insulated neutral and the change to a grounded neutral removed many of the difficulties which we had encountered. Since the neutral was grounded instances have occurred where a portion of the system has become insulated at the neutral during a lightning storm and on such occasions a largely increased number of flash-overs has occurred.

Before the system was earthed, any line fault produced heavy surging with consequent flash-over from live conductors to iron work at various points in the switchgear and arrester gear. Since the neutral has been earthed, these troubles have virtually disappeared. When the system was insulated a fault from one phase to earth did not operate the automatic cut-outs but caused the arrester gear to discharge continuously. This continuous discharging heated the water resistances which are connected in series with the horn gaps of the arresters and as a consequence the discharge at the horn gaps became increasingly vicious until finally something had to give way. Frequently the arc at the horn gaps jumped to neighboring iron work, thus producing a short circuit through the original fault. Great trouble was also experienced due to flash-overs at points on switch-gear and apparatus caused by the surging produced by an arcing ground at the original fault.

By grounding the neutral the automatic cut-outs were able to instantaneously isolate the initial fault. Lightning arrester gear was no longer called upon to continuously discharge and flash-overs on switchgear connections and apparatus became a negligible quantity.

It is of course essential that each separate section of the system shall be separately grounded and provision must be made to ensure that when portions of the system become automatically isolated from other portions, they still remain grounded.

The grounding of the neutral is the only means we adopt for preventing a static rise of potential. In the dry season, during which winds are prevalent, serious rises of pressure would no doubt occur if the neutral of the system were insulated but we have experienced no trouble in this respect since the neutral was grounded.

As already mentioned, the benefits which have been derived from the grounding of the neutral have not been solely due to such grounding but have really been the result of the combination of a grounded neutral with the adoption of differential relays controlling the cut-outs.

With regard to the points at which grounding should be introduced, we have found that generally main generating stations serve the purpose quite satisfactorily, the advantages being as follows:

1. The grounding being at the source of supply there is a minimum length of line between the fault and the source of supply, thus decreasing the total impedance to earth and in the case of a large network, this factor becomes important. In some cases it may be found necessary to introduce more than one ground so as to compensate for the high impedance of the lines where these are unusually long. In practise we have found this to be the case.

2. The grounding resistance being at generating stations, is subject to constant supervision and thus is liable to be kept in a more efficient condition by routine inspection and overhaul, and moreover, can be repaired quickly in case of breakdown with a minimum cost.

3. If the step-up transformers at the station be designed with delta-star connections (the low tension in delta), then grounding can be easily accomplished (without the expense of installing a special earthing transformer), by earthing the star point of the high-tension side.

On the question as to whether a resistance should be inserted in the neutral connection, it may be argued that if the neutral is grounded without a resistance, the pressure rise to earth on the two healthy phases (assuming one phase is earthed through insulator breakdown or other cause) is reduced to a minimum. Grounding solidly, however, results on a fault from one phase to earth, in the production of a dead short circuit with consequent danger to switchgear and other apparatus. The principle we have adopted is to insert resistance of a value as low as safely possible, having in view the condition that the current flowing to any fault must be ample for operating the automatic cut-outs. In this connection it may be found necessary to lower the value in order to compensate for the high impedance of long lines as previously explained or, what amounts to the same thing, to instal another grounded resistance at some other point on the particular section of the system. For example, the ground resistance of the Brakpan 20,000-volt overhead network is 14 ohms and quite satisfactory results have been obtained in practise, but in the case of the Bantjes 20,000-volt overhead network it has been found necessary to have two separate grounding points each of 14 ohms and about 13 miles apart. Originally only one ground resistance was provided at Bantjes distribution station (see Fig. 1) and the experiment was tried of reducing the resistance until ultimately this was brought down to 8 ohms. No marked improvement was however effected owing to the high impedance of the lines between Bantjes and Luipaardsvlei and finally, another grounded resistance was installed at West Rand No. 2. Although no trouble has since been experienced, we are awaiting the results of another lightning season before forming a definite opinion.

In regard to the construction of the resistance, our experience is confined to two types, viz., metallic grid resistances and water resistances and has shown that water resistances are undoubtedly preferable to the metallic type. The latter are liable to burn out in the case of a sustained fault on the system, *e. g.* high resistance fault to earth. This results in great inconvenience especially if it occurs at the commencement of a lightning storm, as the benefit of the grounded neutral is thereby eliminated for the remainder of the storm. We have experienced no trouble with the water resistances but care must be taken to ensure a sufficient body of water and also to provide for a large metallic surface on the entering terminal so as to prevent undue heating and possible boiling of the water. The water resistance we use consists of a large tank about 7 ft. high and 12 ft. in diameter having a submerged terminal of considerable area suspended from an

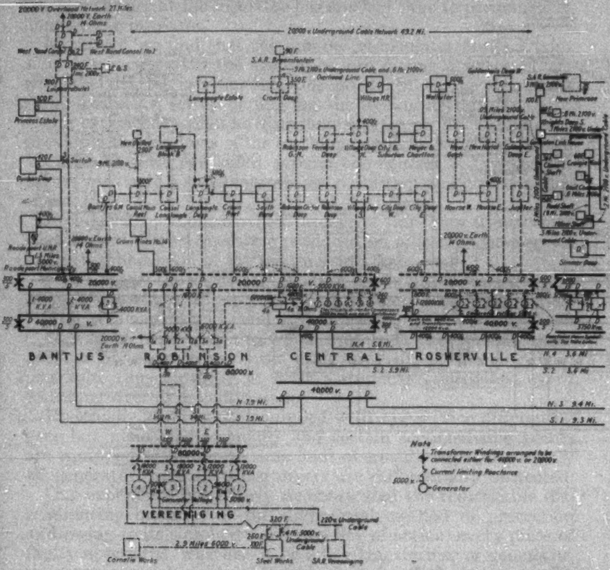
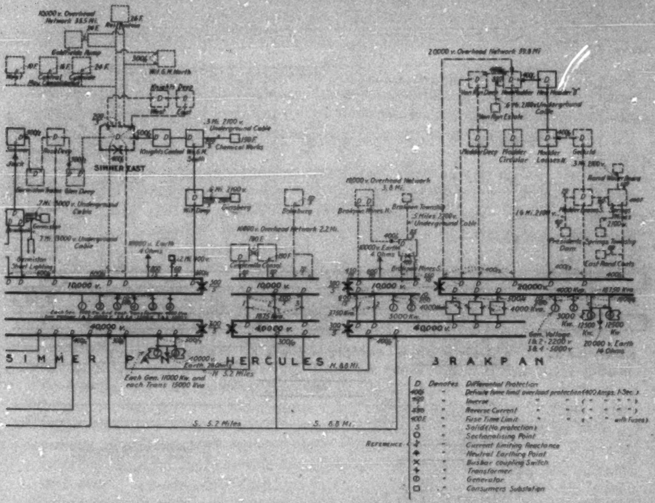

20000 V Overhead Network 27 Miles
20000 V. Earth 14 Ohms
20000 v. Underground Cable Network 43.2 Mi.
West Rand Consol No. 2
West Rand Consol No. 1
S.A.R. Braamfontein
9 Mi. 2100 v. Underground Cable and .6 Mi. 2100 v. Overhead Line
Langlaagte Estate
Crown Deep
Village M.R.
Wolhuter
New Primrose
Princess Estate
New Unified
Langlaagte Block B
Robinson G.M.
Ferreira Deep
Village Deep N.
City & Suburban
Meyer & Charlton
New Goch
New Heriot
Jumpers Deep E.
Switch
Durban Deep
Bantjes G.M.
Consol Main Reef
Consol Langlaagte
Langlaagte Deep
Crown Reef
South Rand
Robinson Central Deep
Nourse Deep
Village Deep S.
City Deep W.
City Deep E.
Nourse W.
Nourse E.
Jupiter
Crown Mines No. 14
Roodepoort U.M.R.
1.5 Miles 3000 v.
Roodepoort Municipality
20000 v. Earth 14 Ohms
Simmer Deep
3 Miles 2100 v. Underground Cable
20000 V.
40000 V.
1-4000 K.V.A.
2-4000 K.V.A.
4000 K.V.A.
6000 K.V.A.
3750 Kva.
20000 v. Earth 14 Ohms
BANTJES
ROBINSON
CENTRAL
ROSHERVILLE
80000 v.
N.4 5.8 Mi.
S.2 5.9 Mi.
N.4 3.6 Mi.
S.2 3.6 Mi.
N 7.9 Mi.
S 7.9 Mi.
N.3 9.4 Mi.
S.1 9.3 Mi.
W
E
80000
12000 K.V.A.
Generator Voltage
5000 v.
VEREENIGING
320 F.
220 v. Underground Cable
2.9 Miles 6000 v.
4 Mi. 5000 v. Underground Cable
Cornelia Works
Steel Works
S.A.R. Vereeniging
Note
Transformer Windings arranged to be connected either for 40000 v. or 20000 v.
Current limiting Reactance
5000 v.
Generator

FIG. 1—DIAGRAM SHOWING SECTIONALIZATION OF SYSTEM OF 3-PHASE

insulator on an erection over the water. Such resistances are placed outside on the ground without housing.

We find that metallic grids require constant supervision whereas the water resistances can be left for a period of six months or more without the value of the resistance altering 10 per cent. The resistance moreover can be varied at will with comparative ease and in first cost is considerably less than the metallic type unless very large resistance values are required.


10,000 v. Overhead Network 38.5 Mi.
Goldfields Pump
Wit. G.M. North
Knights Deep
West
East
SIMMER EAST
.3 Mi. 2100 v. Underground Cable
150 F. Chemical Works
Knights Central
Wit. G.M. South
Rose Deep
Glen Deep
.7 Mi. 3000 v. Underground Cable
Germiston
.7 Mi. 3000 v. Underground Cable
Germiston Street Lighting
10000 v. Earth 4 Ohms
.6 Mi. 2100 v.
Wit. Deep
Geduld
Boksburg
10000 v. Overhead Network 2.2 Mi.
Cinderella Consol
10,000 v. Overhead Network 3.8 Mi.
Brakpan Mines N.
Brakpan Township
.5 Miles 2200 v. Underground Cable
10000 v. Earth 4 Ohms
Brakpan Mines S.
20000 v. Overhead Network 59.8 Mi.
Van Ryn Deep
Modder Deep
Modder Circular
Modder Leases N.
Van Ryn Estate
.6 Mi. 2100 v. Underground Cable
Rand Water Board
1.6 Mi. 2100 v.
Modder Leases S.
Presidents Dam
Springs Township
East Rand Coals
3 Mi. 2100 v.
10,000 v.
10,000 v.
10,000 v.
20,000 v.
40,000 v.
40000 v.
40,000 v.
1875 Kva.
3790 Kva.
3000 Kw.
4000 Kva.
4000 Kva.
3000 Kw.
12500 Kw.
12500 Kw
Gen. Voltage 1 & 2 - 2200 v 3 & 4 - 5000 v
20000 v. Earth 14 Ohms
40000 v. Earth 26 Ohms
Each Gen. 11000 Kw. and each Trans. 15000 Kva
H. 5.2 Miles
H. 8.8 Mi.
S. 5.2 Miles
S. 8.8 Mi.
SIMMER
PAN
HERCULES
BRAKPAN
REFERENCE
D Denotes Differential Protection
400 " Definite time limit overload protection (400 Amps. 1 Sec.)
" Inverse " " (" " " ")
" Reverse Current " " (" " " ")
400E " Fuse Time Limit " " (" " with Fuses)
S " Solid (No protection)
O " Sectionalising Point
" Current limiting Reactance
" Neutral Earthing Point
X " Busbar coupling Switch
" Transformer
" Generator
□ " Consumers Substation

THE VICTORIA FALLS AND TRANSVAAL POWER COMPANY, LTD.
50-CYCLES.

In reference to the earth connection, it is our practise to connect the earth side of the resistance to the station main earth and this has proved quite satisfactory, as in all cases the latter tests out at less than 0.2 ohms.

No difficulty is experienced in obtaining a good earth at power stations as all our stations are associated with a large expanse of water and large metallic plates sunk in the water provide a good earth at all times of the year.

The combination of an earthed neutral (through resistance) with the differential system of automatic cut-outs has greatly reduced the insulator troubles.

It must be remembered that the majority of our insulator troubles are caused by lightning and as the system is subjected for nearly six months in the year to very severe lightning effects, the matter is of much importance. Owing to the combined action of the earthed neutral and the instantaneous operation of the differential relays the lines which trip out due to lightning flash-overs are in the majority of cases, fit to close it again, because the arc at the insulator has not had time to permanently damage the insulator.

Moreover, we find that the number of insulator faults is considerably increased if the system be run during a severe storm with the neutral ungrounded, due no doubt to the secondary surging which is set up finding out the weaker insulators.

Our experience is that no disturbance to telephones is produced, providing the windings of the earthing transformer are star-delta. We find that we can safely ground the neutral at two distant points with only a small interchange of current and no secondary effects.

If the system is not earthed through a star-delta transformer very violent disturbances are produced on all telephone circuits in the neighborhood of the transmission lines.

Fig. 1 shows the electrical layout of the high-tension lines and apparatus and also the location of all protective devices, current limiting reactances and points of earthing.

Vol. 35
1916

It will be seen that the whole system is subdivided into a number of separate networks each laid out on the ring-main principle, thus ensuring at least a duplicate supply to every consumer over divergent routes.

Practically all lines are equipped with Merz-Price differential gear but main feeding points and certain sectionalizing points are equipped with difinite time-limit overload relays, also nearly all generators and all transformers are differentially protected.

Our experience has clearly demonstrated the remarkable discriminating qualities of the differential method of protection and owing to its simplicity and rapidity of action, every piece of faulty apparatus, whether it be a line transformer or generator, is instantaneously isolated with minimum disturbance to the system. It is a feature of this method, however, that individual pieces of apparatus are separately protected and as a consequence a fault on the busbars does not come within the control of the differential relays. Such faults are or should be extremely rare but in order to limit their effect upon supply, the networks are divided up into sections, each section being under the control of definite-time-limit relays at the points where it is fed and where it is inter-connected with neighboring sections. Inverse-time-limit overload relays are in use at a few points where discrimination with other relays is not required. Our experience has proved that on a large power system such relays are of little value as a discriminating device. Reverse-current relays are in use on a few points such as generators not provided with differential protection and isolated lines not forming a part of a ring-main network and not differentially protected.

It will be noticed in Fig. 1 that the setting of the definite-time-limit overload relays at different points on a network is such that under heavy fault conditions the network is automatically sectionalized, each section capable of a separate existence, *i. e.*, each of these sections has sufficient feeders to deal with its particular loading. These conditions apply to the worst type of fault, namely, a busbar fault at a substation, all feeder faults being dealt with instantaneously by differential protection and without operating overload relays at other points.

In the event of a sustained fault on consumer's premises the substation transformers are tripped off by the simple device of a small fuse inserted in the secondary circuits of the differential relays. This fuse blows with small time element and brings the instantaneously acting differential relay into operation thereby tripping the transformers without operating overload relays at other points on the system. Faults of this kind frequently occur and the supply to the consumer's fault is always isolated without affecting the supply to others.

We use the current flowing to ground at the neutral connection to indicate when a fault to earth occurs. For this purpose a recording ammeter is connected to the secondary side of a current transformer in the earth connection. The results obtained are purely qualitative.

From tests taken with the oscillograph, we have found that under normal operation the magnitude of the current flowing to earth through the neutral is relatively small and of no practical importance.

We have also found that with the neutral earthed simultaneously at two different points, the interchange of current is not appreciable enough to be serious. For example on the 40,000-volt system with the neutral earthed at Simmerpan through 28 ohms, the r.m.s. value of the current was found to be about 1 ampere and the current flowing through the neutral of the Simmerpan 10,000-volt network (neutral resistance 7 ohms.) less than 0.2 amperes.

The oscillogram of the former showed the presence of at least the 13th harmonic and the latter showed the presence of at least the 23rd harmonic.

With the neutral of the 40,000-volt system earthed at two distant points, we found the presence of a comparatively large amount of even harmonics, the 6th being predominant and over 20 per cent of the fundamental in value and in phase with it.

The following is a short description of the various types of relays in use on the system:

Differential Relay. This device as used on our system is a three-phase three-pole relay consisting essentially of a three-pole armature rotating in a three-pole field system.

The latter is energized from the secondary side of the differential protective current transformers and causes the movement of the armature.

The armature in its rotation releases a weighted contact arm which closes the switch-tripping circuit.

Definite-Time-Limit Overload Relay. This relay is made in two parts, one part consisting of an overload relay and the other comprising the definite-time-limit mechanism.

The overload relay is similar in design to the three-pole differential relay, excepting that the impedance of the coils is much greater.

The definite-time-element portion commences to operate when a d-c. circuit is closed by the overload portion which starts the clock-work mechanism. After the pre-determined time has elapsed the relay closes the switch-tripping circuit.

Inverse-Time-Limit Overload Relay. This relay is of the ordinary induction type instrument and the armature, consisting of the usual metal disc, rotates in a field system energized by the secondary circuit of the line current transformers. The relay is single phase and three are required for full protection.

The time element is obtained by varying a tension spring controlling the armature.

Reverse-Current Relay. The reverse-current relay (or more correctly reverse-power relay) is exactly similar in construction and operation to the inverse-time-limit overload relay excepting that it has pressure coils in addition.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 27, 1916.

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EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED STATIONARY INDUCTION APPARATUS

BY V. M. MONTSINGER

Abstract of Paper

The paper falls logically into three divisions: (1) A general review of the principal laws of the dissipation of heat,—radiation, conduction and convection. (2) the development of a simple formula for the effect of altitude on the cooling of surfaces of different shapes, and (3) a general discussion of the method of conducting experimental observations at different altitudes, on three different shaped surfaces.

1. The first division is principally historical in that the most reliable data is given as found from former laboratory investigations, to determine (a) the laws of heat dissipation and (*b*) the effects of various factors on these laws. This is given as a preparatory step to determining the formula in division 2.

2. It is shown in the second division that, where the loss by convection varies as the 1.25 power of the temperature rise and as the 0.5 power of pressure, the " temperature rise " varies as the 0.4 power of pressure. It is then shown that the temperature rise increases, in going from a lower to a higher altitude, at a uniform rate of about 5 per cent for each 1000 meters change in elevation.

Since this applies only to loss of heat by convection, a correction factor is added to reduce this effect when radiation (same in vacuo as in gas) enters into the dissipation of heat. This factor is first expressed in percentage of convection loss to total loss, and then expressed in terms of the developed surface effective for convection, and the envelope surface effective for radiation. This is called the " shape-factor" S. The percentage increase in temperature then is equal to $5\ AS$ where A is the difference in altitude expressed in kilometers.

The above is for a loss unaffected by temperature. Where the loss is in copper windings, an increase in temperature, due to changes in pressure, has the effect of increasing the loss, which in turn still further increases the temperature rise.

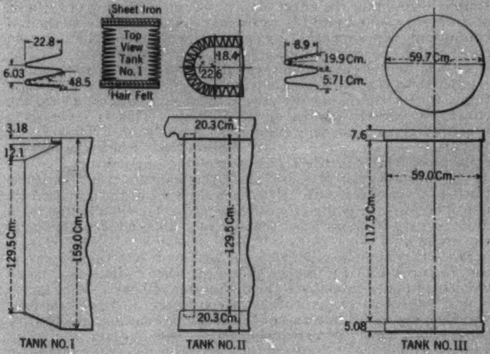
It is shown by mathematical treatment that this effect increases the value $5\,AS$ to $5.85\ AS$ for all copper loss. For various ratios of copper to iron loss (unaffected by temperature), the term becomes, close enough for practical purposes, $AS\ (5 + a)$, where a is percentage of copper loss to total loss. The calculated values are then compared with the observed values.

3. In this division the method of carrying on the experimental observations is gone into somewhat in detail.

Introductory

WHILE we have reliable data, obtained from laboratory investigations, on the effect of rarefied atmospheres on each of the three principal modes of heat dissipation—radiation conduction and convection,—yet there does not seem to be any data on, or record of, an investigation to determine this effect when various combinations of the above modes enter into the dissipation of heat, such as we usually have in self-cooled induction apparatus.

Since there is a wide range of these combinations, it would be impossible to make experimental observations on each one. Tests conducted on a few combinations should give us sufficient data with which to make calculations for the remaining ones. Calculations, of course, can be made only by making use of the known effect of altitude on each mode entering into the dissipation of heat; and at the same time we must know fairly accurately



22.8
6.03
48.5
Sheet Iron
Top View Tank No. 1
Hair Felt
18.4
22.6
8.9
19.9 Cm.
5.71 Cm.
59.7 Cm.
3.18
12.1
129.5 Cm.
159.0 Cm.
20.3 Cm.
129.5 Cm.
20.3 Cm.
7.6
59.0 Cm.
117.5 Cm.
5.08
TANK NO. I
TANK NO. II
TANK NO. III

FIG. 1

the proportion of heat emitted by each mode, *i.e.*, we should know its law.

The law of radiation has been accurately determined by Stefan and Boltzman, whence it derives its name, "Stefan-Boltzman law." The law of conduction is well known but need not be considered in this discussion because rarefied atmospheres do not affect it, and for stationary electrical apparatus the dissipation of heat takes place almost entirely by radiation and convection, the latter, excepting for plain surfaces, playing the more prominent part. A law for the convection of heat has been developed and is given by Dr. Irving Langmuir in some of his publications.* While this law holds remarkably well for high temperatures, yet for low temperatures, *i. e.*, from 0 to approximately 100 deg. cent., it does not seem to hold very well. This is shown later and in fact is pointed out by Dr. Langmuir himself.

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*TRANS. A. I. E. E. Vol. XXXII, Part I, p. 301; Amer. Electrochem. Soc. Apr. 1913.

The object of this paper is (1) to give, as found from experimental observations on surfaces of various shapes, the ratio of heat dissipated by radiation to that dissipated by convection, thus making it possible to predict the effect of altitude on the cooling of surfaces of different shapes, such as are found in stationary electrical apparatus, and (2) to give the results of experimental observations conducted on transformers (Fig. 1) under natural atmospheric conditions at different altitudes ranging from 305 m. (1000 ft.) to 3360 m. (11,000 ft.) These observed values are compared with theoretical calculations, making use of the established laws of the effect of barometric pressure on the principal modes of heat dissipation, namely, radiation, conduction and convection. From this a simple formula is developed, expressing the effect of altitude on the cooling of surfaces of various shapes.

GENERAL LAWS OF RADIATION, CONDUCTION AND CONVECTION OF HEAT

RADIATION OF HEAT

The Stefan-Boltzman law that the radiation from a black body is proportional to the difference of the fourth powers of the absolute temperatures has withstood very rigid experimental investigations and can be considered as accurate. The Stefan-Boltzman law as applied to the radiation of heat from a body may be expressed

$$W_r = K\, e\, (T_2^4 - T_1^4) \qquad (1)$$

where W_r = watts radiated per sq. cm. of surface.

K = an empirical constant.

e = relative emissivity which depends on the nature and color of the surface.

T_2 = absolute temperature of the radiating surface.

T_1 = absolute temperature of the room.

The exact value of K has not been definitely determined at present, but 5.7×10^{-12} (probably the most commonly accepted value) has been used in making calculations to check the experimental observations on surfaces of various shapes. To quote from Dr. Langmuir (TRANS. A. I. E. E. Vol. xxxii, 1913 p. 309.)

" The radiation constant, 5.7, is subject to some uncertainty at present. For several years, the commonly accepted value was 5.32, which was the result obtained by Kurlbaum (*Wied. Am.* 65, 746, 1898). Recently, however, (1909), Fery obtained a value 6.3. Since then many investigators have redetermined this constant. Paschen and Gerlach (*Ann. d Physik*, Vol. 38, p. 30, 1912) obtained the value 5.9. Shakespeare (*Proc. of the Roy. Soc.*, Vol. 86A, p. 180, 1911) obtained 5.67. Within the next year or so the correct value of this constant will undoubtedly be determined. For the present, it would seem almost certain that the value 5.32 is too low, and that the value 5.7 must be fairly close to the true value."

EFFECT OF PRESSURE, COLOR AND CONTOUR OF SURFACE ON RADIATION

Since radiation of heat is purely a surface phenomenon, it is proportional only to the envelope of the surface and is independent of the pressure of gas. In other words, for a surface of an irregular contour it is the outer area, that is effective for radiation, and the rate of radiation is the same in vacuo as in a gas, all other conditions being the same.

For surfaces that are not black the heat radiated is always less than that of a perfect black body. The following tabulation, by Langmuir, taken from Table VII Trans. of the Am. Elec. Soc. Vol. 23-193, gives in part for various colored surfaces the relative emissivities *e* as percentage of that from a black body.

	Relative Emissivities *e*			
Temperature deg. cent. (room 27 deg.)	52	77	127	mean
Copper oxidized	77	70	76	74
Copper calorized	39	28	26	31
Silver (calculated)	1.7	1.9	2.1	1.9
Cast iron bright	17	20	23	20
Cast iron oxidized	50	67	64	60
Aluminum paint	67	60	45	57
Gold enamel	33	40	37	37
Monel metal bright	50	55	38	47
Monel metal oxidized	50	60	49	56

Again, if a surface is irregular such as we have in corrugated tanks for self-cooled transformers and the color is considerably different from a perfect black, the heat radiated from the cavities is greater than that radiated from a flat surface. This is due to the fact that besides the heat dissipated by direct radiation, additional heat is thrown out by reflection. However, the color of the surfaces of the tanks used by the writer in the experimental observations (and also for practically all commercial transformers) was practically a lamp black, and e has been considered as unity, *i.e.*, no attempt has been made to make corrections for the color when making theoretical calculations. A small error may have been introduced due to this effect, but in general for surfaces of this color the error should be negligible.

CONDUCTION OF HEAT

Since conduction of heat takes place by transference from one part of one body to another part of the same body without bodily transfer, this mode of heat transmission has very little, if any, effect on the change in temperature of stationary induction apparatus due to changes in barometric pressures. In other words, it is not necessary to consider it in this discussion. In general, however, for a steady flow of heat through a solid of uniform material the following law holds:

$$W = \frac{KA}{l}\,(T_2 - T_1) \qquad (2)$$

Where W = watts of heat flow
K = coefficient of heat conductivity
A = area of cross section
l = length of conductor
$(T_2 - T_1)$ = temperature difference causing flow of heat.

CONVECTION OF HEAT

Within the last four or five years Dr. Langmuir has done considerable work upon, and has developed a formula for, the convection of heat. His formula is based on the film theory, in which he assumes that the dissipation of heat takes place by first being conducted through a film of adhering gas, to the surrounding medium where it is carried away by convection air currents. The formula is expressed in the form

$$W_c = \frac{\phi_2 - \phi_1}{B} \qquad (3)$$

Where W_c = Watts dissipated per sq. cm. surface
B = thickness of adhering film

and ϕ is a function of T (the absolute temperature) of the form

$$\phi = 1.93 \times 10^{-6} (1 + 0.00012\, T) \left[2/3\, T^{3/2} - 248\, T^{1/2} + 2760 \tan^{-1} \sqrt{\frac{T}{124}} \right]$$

From experimental observations, Dr. Langmuir found that for temperatures greater than 100 deg. cent. the value of B is 0.45 cm. Observations made throughout a wide range of high temperatures agree remarkably well with calculations using this empirical constant; but for low temperatures, of approximately 100 deg. cent. and less, he found it necessary to give B values greater than 0.45 cm. For example, for a 25 deg. cent. rise above 27 deg. room temperature, B had the value of 0.58 cm. and for temperature rises between 25 deg. cent. and 75 deg. cent. B ranged between 0.45 cm. and 0.58 cm. Since 0 deg. to 100 deg. cent. usually covers the temperature range found in self-cooled induction apparatus, this formula would not give correct results unless supplied with different values of B for different temperature values.

In 1817, Dulong and Petit announced the following law as a result of their experiments conducted over a rather limited range of temperatures.

> The velocity of the cooling due solely to the contact of a gas is proportional to the excess of temperature in degrees centigrade raised to the power 1.233.

This was later verified by Peclet.

Lorenz (*Ann. d. Physik*, Vol. 13, p. 582, 1881) by making certain assumptions derived for convection of heat from vertical plane surfaces the following formula:

$$W_c = 0.548 \sqrt[4]{\frac{c\, g\, K^3}{h\, H\, \theta_1}}\, \rho^{0.5}\, \theta^{1.25} \qquad (4)$$

where W_c = heat convection per sq. cm. of surface

c = specific heat of gas at constant pressure

K = its thermal conductivity

h = its viscosity

θ_1 = its average temperature in deg. cent.

ρ = its average density

g = gravitational constant

θ = difference in temperature of plane surface and of the gas at a great distance from the plane.

H = height of plane.

For 30 deg. cent. room temperature and for standard atmospheric pressure the above formula reduces to

$$W_c = 3.98 \times 10^{-4}\, H^{-\frac{1}{4}}\, \theta^{1.25} \qquad (5)$$

The results of observations conducted by the writer indicate that the loss vs. temperature rise follows a simple exponential law similar to Lorenz' formula (when H = approx. 9 cm.) throughout a range of temperatures from 0 deg. cent. to approximately 100 deg. cent. (tests were not made above 100 deg. cent.). This law also holds in plotting on logarithmic paper, the maximum oil rise of tanks with surfaces of various shapes against the loss dissipated per unit area of developed surface. Referring to Fig. 2 in which maximum oil rise is plotted on a logarithmic scale against loss per unit area of the developed surfaces of three tanks shown in Figs. 3 and 4, it will be noted that these points fall (for each tank) practically in a straight line. Providing the temperature gradients along the tank surfaces from top to bottom do not change for different maximum oil rises (and there is no reason why they should appreciably change) the equation of the line drawn through these points for any one tank, when supplied with the proper constant, (found

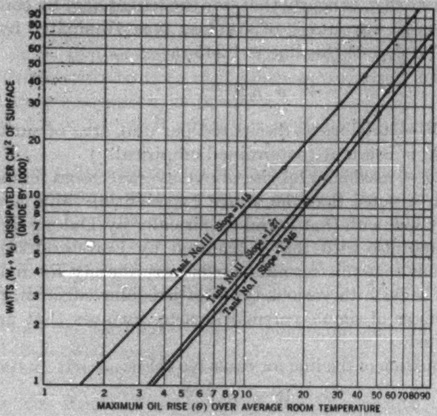

FIG. 2

by trial), gives us the law of heat dissipation for that particular tank. This equation, however, includes here both radiation and convection.

Using an empirical formula for convection somewhat similar to equation (**5**), calculations indicate that tank No. 1 dissipated approximately 85 per cent of its loss by convection and 15 per cent by radiation; that tank No. II dissipated approximately 65 per cent of its loss by convection and 35 per cent by radiation; while tank No. III (plain), dissipated approximately 43.5 per cent of its loss by convection and 56.5 per cent by radiation.

The equation based on maximum oil rise for tank No. I should therefore be that, or nearly that, for the loss of heat by convection since a small percentage of its loss was dissipated by radiation. The slope of this line is 1.245 or

$$W = K\theta^{1.245} \tag{6}$$

where W = total watts dissipated per unit area of surface
K = constant (determined empirically)
θ = maximum oil rise above average room temperature

It will be noted that the above exponential value agrees remarkably well with that found empirically by Dulong and Petit (1.233) and also with that calculated by Lorenz (1.25). The writer finds that this formula holds very closely for maximum oil rise of tanks with various types of irregular surfaces, ranging from surfaces of simple corrugations to surfaces that are very complicated.

The equation of the line for tank No. II is

$$W = K\,\theta^{1.27} \tag{7}$$

and for tank No. III (plain surface)

$$W = K\,\theta^{1.15} \tag{8}$$

If we take from Fig. 6 (radiation curve) the temperature rise line based on 30 deg. or 35 deg. cent. room temperature and plot it on logarithmic paper, we obtain, between the limits of 10 deg. and 50 deg. rise, a line whose equation is approximately

$$W_r = K\,\theta^{1.12} \tag{9}$$

The exponent in equation (**8**) which involves approximately equal values of radiation and convection falls between the values 1.12 and 1.245, as would be expected. However, the temperature range from which equations (**7**) and (**8**) were based is not as wide as that on which equation (**6**) is based and for this reason they are probably not as accurate. Refering to Fig. 2, it will be noted that equation (**6**) is based on four observed points. The lower one was obtained in Pittsfield only for the purpose of determining a more accurate exponential value, and therefore this test was not repeated at the higher altitudes. For temperatures within the range of the operation of stationary induction apparatus, the convection for vertical surface can no doubt be expressed within a reasonable accuracy by the simple equation

$$W_c = K\,\theta^{1.25} \qquad (\mathbf{10})$$

where W_c = watts dissipated per sq. cm. of surface (developed)
K = constant (found by trial to be 2.32×10^{-4} for tanks No. II and III and 2.04×10^{-4} for tank No. 1)
θ = temperature rise in deg. cent.

It is interesting to note that when we substitute 9.0 cm. for H in Lorenz's equation, it becomes

$W_c = 2.3 \times 10^{-4}\,\theta^{1.25}$ which is practically the same as equation (**10**).

Equation (**10**) is used later in comparing calculated values of loss by convection with the input loss less the calculated loss by radiation for three different styles of tanks. Also it is used in deriving a formula for expressing the effect of altitude on the cooling of surfaces of various shapes. It should be noted that it is not intended that this formula be applied for high temperatures where the formula $\dfrac{\phi_2 - \phi_1}{B}$ holds, but only for low temperatures of 100 deg. cent. and less.

EFFECT OF ROOM TEMPERATURE ON DISSIPATION OF HEAT

(*a*) *Radiation.* Referring to Fig. 6 it will be seen that room temperature has an appreciable effect on radiation. For example, for a 50 deg. rise the loss radiated in the presence of a 15 deg. cent. room temperature is 0.0354 watts per sq. cm., while in a 35 deg. cent. room temperature, the loss is 0.0427 watts per sq. cm.—a difference of 20 per cent, or 1 per cent per deg. variation in room temperature. For this reason an attempt was made to hold as nearly as possible the same room temperatures at the three different altitudes.* The room temperatures were the same at both Pittsfield and Leadville, while, due to encountering a period of very warm weather at

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*See p. 621 for locations.

Boulder, it was necessary to hold a room temperature from one to six degrees higher than that held at the other two places.

(*b*) *Conduction*. Room temperature should have no effect.

(*c*) *Convection*. According to Dr. Langmuir's equation, $\frac{\phi_2 - \phi_1}{B}$, (plotted in Fig. 5) room temperature has very little effect on convection. No attempt has been made to add a room temperature correction factor in equation (**10**).

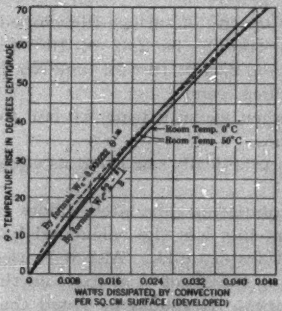

FIG. 5

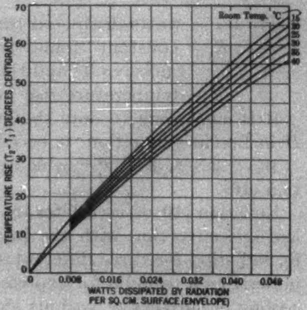

FIG. 6

EFFECT OF BAROMETRIC PRESSURE ON RADIATION CONDUCTION AND CONVECTION

(*a*) *Radiation*. Since radiation does not depend on the density of the surrounding air, changes in barometric pressure have no effect on it.

(*b*) *Conduction*. Changes in pressure do not affect conduction.

(*c*) *Convection*. In 1817 Dulong and Petit found that the velocity of cooling in a gas was proportional to the pressure raised to the power

0.45 for atmospheric air.
0.38 for hydrogen
0.517 for carbonic acid.
and 0.501 for olifiant gas.

Messrs. Kennelly and Sanborn[*] in an investigation on "The

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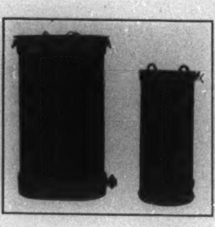
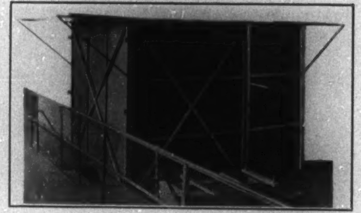
[*] *Proc. Am. Phil. Soc.* Vol. liii, 1914.



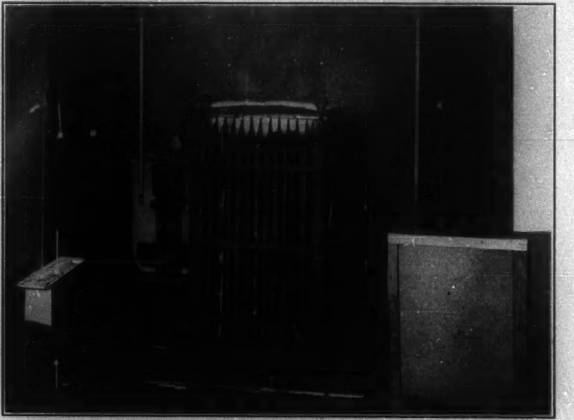
[MONTSINGER]

FIG. 3—CORRUGATED AND PLAIN TANKS USED FOR HEAT TESTS TO DETERMINE EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED TRANSFORMERS



[MONTSINGER]

FIG. 8—PRESSBOARD HOUSING USED FOR MAKING TESTS TO DETERMINE EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED TRANSFORMERS



[MONTSINGER]

FIG. 4—SHOWING TANK NO. 1 IN HEAT RUN POSITION

Influence of Atmospheric Pressure upon the Forced Thermal Convection from Small Electrically Heated Platinum Wires," found that the linear convection is nearly proportional to the 0.5 power of the atmospheric pressure.

Compan found that for spheres 2 cm. in diameter, convection varies as the 0.45 power of the pressure. According to Lorenz's equation, convection varies as the 0.5 power of the pressure. In making calculation later on, the writer has used the value 0.5.

EFFECT OF POSITION, SHAPE OF CONTOUR, AND HEIGHT OF PLANE ON CONVECTION

Dr. Langmuir found that the convection was about 10 per cent more for the upper, and 50 per cent less for the under side of a horizontal plane than for a vertical plane. (NOTE: the covers for the tanks used in the experimental observations were insulated thermally from the horizontal surfaces so that practically no heat was lost by them, thus eliminating the necessity of making corrections when comparing input with calculated loss.)

Calculations indicate that the convection is practically the same for a plain surface, 130 cm. (51 in.) in height as for a surface having corrugations 8.9 cm. (3.5 in.) in depth, 5.72 cm. 2.25 in.) pitch and 130 cm. (51 in.) in height; but that the convection is approximately 15 per cent less for a surface having corrugations 22.8 cm. (9 in.) in depth, 6.03 cm. (2 3/8 in.) pitch and 140 cm. (55 in.) in height with upper and lower air spaces open for free circulation of air.

Again according to Lorenz's equation, convection varies inversely as the height of a vertical plane raised to the ¼ power ($H^{-1/4}$). Observation of tests made on vertical surfaces whose heights range from one or two meters to four or five meters indicate that the ¼ power is too large. In fact experience indicates that for simple corrugations and for heights ordinarily used for cooling of stationary induction apparatus, the effect of height is practically negligible. As an evidence that the ¼ power of the height is too great, if we substitute 130 cm. (corresponding to the heights of tanks used in the observations)for H in Lorenz's formula it becomes:

$$W_c = 1.18 \times 10^{-4}\ \theta^{1.25}$$

Referring to equation (**10**) it is seen that if we had used Lorenz's formula the calculated loss would have been only about 50 per cent of the loss actually found in the observation. But as pointed out before for a height of 9 cm. the formula gives practically the same results as equation (**10**).

METHOD OF CALCULATING LOSS DISSIPATED FROM TANK SURFACE

For theoretical calculations, the temperature of the surfaces having corrugations was taken as an average of the temperature of the outside and inside bends. If the equations for radiation and for convection were not in exponential form, *i.e.*, if loss plotted against temperature rise were straight lines, it would only be necessary to determine the average temperature of the surface and this multiplied by the areas would give us the predicted losses by convection and by radiation. Again if we had an equation of the temperature gradient from the top to the bottom of the surface of each tank we could substitute in the general heat equations and integrate between limits, for calculating the losses. However, it would probably be a long and tedious task to derive an equation for the temperature gradient of the surface.

The most convenient method, (and the one used by the writer) is to use the process of summation, *i.e.*, to divide the area of the surface into sections for every few deg. rise, and calculate the loss for each section separately. The sum of the losses for the sections should be the total calculated loss. If the surface is divided into enough sections the error introduced is negligible.

Table I shows a comparison of the input loss (at Pittsfield) with calculated losses using the equations:

$$W_r = 5.7 \times 10^{-12} (T_2^4 - T_1^4) \qquad \text{for radiation}$$
$$W_c = K\, \theta^{1.25} \qquad \text{for convection}$$

and $$W_c = \frac{\phi_2 - \phi_1}{0.45 \text{ cm.}} \qquad \text{for convection.}$$

The table shows, with the exception of the plain tank, that the equation $\frac{\phi_2 - \phi_1}{B}$ gives too high loss at lower temperatures, but that as the temperature increases the calculated and test values come close together, which indicates, as pointed out before, that B has a greater value than 0.45 cm. for low temperatures. For the plain tank the losses are so small, especially for test 7 that a few watts in observable errors would make a large error.

TABLE I.
COMPARISON OF CALCULATED LOSS WITH TESTS CONDUCTED AT PITTSFIELD.

Test	Max.* oil rise deg. cent.	†Ave. test watts input	Watts loss by convection			
			Tested (Input watts less calc. rad.)	Calculated by equations $W_c =$		
				$\frac{2.04\,\theta^{1.25}}{10^4}$	$\frac{2.32\,\theta^{1.25}}{10^4}$	$\frac{\phi_2 - \phi_1}{0.45\text{ cm.}}$
		TANK No. I.				
1	21.1	1564.5	1268.0	1245.0	1413.0	1757.3
2	34.6	2910.0	2370.0	2380.0	2709.5	2985.0
3	50.9	4721.0	3811.0	3830.0	4461.0	4561.2
		TANK No. II.				
4	24.9	1550.	1023.4	......	1005.0	1266.
5	42.3	3114.0	2114.0	......	2041.0	2297.0
6	56.7	4500.0	3026.2	......	3129.0	3200.0
		TANK No. III.				
7	15.6	347.5	186.5	......	100.0	144.
8	41.9	1064.5	478,0	......	446.5	480.0
9	60.2	1657.5	704.5	......	722.3	735.1

*Based on the following average ambient temperatures:

For tests No.	1	2	3	4	5	6	7
Room (deg. cent)	30.0	30.1	32.0	30.0	32.0	32.0	29.9
Test No.	8	9					
Room (deg. cent.)	30.2	30.1					

†Ave. of volt × ampere and wattmeter readings.

THEORETICAL CALCULATION OF EFFECT OF PRESSURE ON COOLING

We now have sufficient data with which we should be able to predict fairly closely the increase in temperature of self-cooled stationary induction apparatus. Assuming that the loss dissipated by convection W_c varies as the 0.5 power of the barometric pressure, and as the 1.25 power of the temperature rise, and letting ρ equal the barometric pressure in mm. of mercury, the general equation for convection becomes

$$W_c = K\,\theta^{1.25}\,\rho^{0.5}$$

or

$$\theta^{1.25} = \frac{1}{K}\,\frac{W_c}{\rho^{0.5}}$$

$$\theta = K_1\,\frac{W_c^{0.8}}{\rho^{0.4}}$$ or compared with ρ at sea level

$$\theta = K_1\,W_c^{0.8}\left(\frac{760}{\rho}\right)^{0.4}$$

For a constant loss the temperature rise therefore varies inversely as the 0.4 power of the pressure.

Using the Smithsonian Institute's formula changed from English to metric system for altitude vs. barometric pressure, namely

$$\log_{10} \rho = \log_{10} 760 - \frac{A}{19.07377\,[1 + 0.00367\,(T - 10)\text{ deg. cent.}]} \qquad \textbf{(11)}$$

where

ρ = barometric pressure in mm. of mercury.
A = altitude in kilometers.
T = temperature in deg. cent. = 30 deg.

we obtain the following values:

when ρ =	760	711	664	621	570	542	507	474	mm.
or 1,000 A =	0	600	1200	1800	2400	3000	3600	4200	m.
% increase in θ =	0	2.72	5.6	8.75	11.4	14.60	17.52	20.9	
$\frac{\%\text{ increase in }\theta}{A}$ =	0	4.53	4.66	4.86	4.86	4.86	4.86	4.97	

The average of the above values is 4.8. With an average positive error (when A is greater than 1.2) of about 2.5 per cent, we may put

$$\phi_1 = 5\,A \qquad \textbf{(12)}$$

where ϕ_1 is the percentage increase in temperature rise for a constant loss and A is the difference in altitude between lower and upper elevations expressed in kilometers (*i.e.*, for 1000 m. $A = 1$).

EFFECT OF PRESSURE ON SURFACE DISSIPATING PART OF LOSS BY RADIATION AND PART BY CONVECTION

Equation (**12**) is applicable only for a surface dissipating all its loss by convection when naturally cooled. However, this condition seldom exists in commercial transformers.* The percentage of total loss by convection is probably from 40 to 45 per cent for a plain surface, whereas for surfaces with very complicated contours the loss by convection may approach more nearly 100 per cent. It follows, therefore, that the effect of altitude will be quite different for different types of surfaces—each one requiring special consideration.

This effect may be expressed in terms of the percentage of loss by convection to the total loss. For example, if only 50 per cent of the loss is by convection and the remaining by radiation (unaffected by pressure) the effect of pressure will be approximately one-half that expressed by equation (**12**). Letting ϕ_2 equal the percentage increase in temperature rise for surfaces having both radiation and convection, we have

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*Natural draft transformers would come under this condition where the total RI^2 loss is carried away by natural circulation of air through ventilating ducts in the windings.

$$\phi_2 = 5\,A \times \frac{\text{loss by convection}}{\text{total loss}}$$

or

$$\phi_2 = 5\,A \times \frac{W_c}{W_c + W_r} \qquad (\mathbf{13})$$

where W_c is the convection loss per unit area of developed surface and W_r is the radiation loss per unit area of envelope surface.

Since the ratio between W_c and $(W_c + W_r)$ does not remain quite the same when the altitude changes, equation (**13**) is not quite correct. For instance, when the apparatus is taken to a higher altitude the radiation increases while the convection may decrease. However, the error is small especially for surfaces with irregular contours such as corrugations, etc., where the greater part of the loss is by convection, and since it is a positive error, *i. e.*, it makes the estimated temperature rise slightly higher than it should be, it may be neglected for practical purposes. An attempt to correct for it would require an equation very cumbersome to handle.

If we assume a standard room temperature and a standard temperature rise, we can, for practical purposes, express W_c and W_r in terms of the developed and envelope surfaces reduced to equivalent values of loss per unit area. This makes it more convenient for practical application. For example, referring to Figs. 5 (either formula for convection) and 6 we find that for a 50 deg. rise above a 30 deg. room temperature the calculated watts dissipated per sq. cm. of surface are approximately in the ratio of 1.0 for convection to 1.3 for radiation.

We may therefore restate equation (**13**)

$$\phi_2 = 5\,AS \qquad (\mathbf{14})$$

where S = shape factor = $\dfrac{\text{developed surface of tank}}{(\text{dev.} + e\,1.3 \times \text{envelope})\ \text{surfaces.}}$

DERIVATION OF GENERAL EQUATION FOR EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE

We have seen that for temperature rises between 0 deg. and 75 deg. cent., the general equation of temperature rise vs. loss is $\theta = K W^n$ and that the equation of temperature rise vs. altitude is $\phi_2 = 5\,AS$. If we let θ = temperature rise at some high altitude, and

let W_0 = loss at room temperature θ_0 for given load conditions on the transformer

" W = loss at temperature rise θ

" $a = \dfrac{\text{copper loss}}{\text{(iron + copper) loss}}$

We may put $W_0 = W_0\,(1 - a) + a\,W_0$

Since iron loss is practically unaffected by temperature (see TRANS. A. I. E. E., 1912, p. 2025, MacLaren) at temperature θ (for temperature coefficient of resistivity of copper of 0.00427 per cent per deg. cent.) the copper loss $= a\,W_0\left(\dfrac{234 + \theta_0 + \theta}{234 + \theta_0}\right)$

$$\text{Then}\quad W = W_0\,(1 - a) + a\,W_0\left(\frac{234 + \theta_0 + \theta}{234 + \theta_0}\right)$$

$$= W_0\left(\frac{234 + \theta_0 + a\,\theta}{234 + \theta_0}\right)$$

The temperature rise (say θ_x) for this loss at sea level will be

$$\theta_x = K\,W_0^n\left(\frac{234 + \theta_0 + a\,\theta}{234 + \theta_0}\right)^n$$

If taken to a high altitude the temperature rise, with this loss, will be increased ϕ_2 per cent *i. e.*,

$$\theta = \theta_x + \frac{\phi_2}{100}\,\theta_x = \theta_x\left(1 + \frac{\phi_2}{100}\right)$$

$$= K\,W_0^n\left(1 + \frac{\phi_2}{100}\right)\left[\frac{234 + \theta_0 + \theta\,a}{234 + \theta_0}\right]^n$$

Let θ_s = temperature rise at the lower altitude for the given load conditions.

$$\theta_s = K\,W_s^{\,n}$$

$$= K\,W_0^{\,n}\left(\frac{234 + \theta_0 + a\,\theta_s}{234 + \theta_0}\right)$$

then $$\frac{\theta}{\theta_s} = \left(1 + \frac{\phi_2}{100}\right)\left[\frac{234 + \theta_0 + a\,\theta}{234 + \theta_0 + a\,\theta_s}\right]^n$$

Which may be written in the form

$$\frac{\theta}{\theta_s} = \left(1 + \frac{\phi_2}{100}\right)\left[\frac{234 + \theta_0 + a\,\theta_s + a(\theta - \theta_s)}{234 + \theta_0 + a\,\theta_s}\right]^n$$

Putting $\left(1 + \dfrac{\phi_2}{100}\right) = B$

and $$234 + \theta_0 + a\,\theta_s = D$$

$$\frac{\theta}{\theta_s} = B\left[1 + \frac{a\,(\theta - \theta_s)}{D}\right]^n$$

Expanding by the binomial theorem

$$\frac{\theta}{\theta_s} = B\left[1 + n\,\frac{a\,(\theta - \theta_s)}{D} + \frac{n\,(n-1)}{2}\cdot\frac{a\,(\theta - \theta_s)^2}{D^2} + .\right.$$

The terms after the second may be neglected without any appreciable error, then

$$\frac{\theta}{\theta_s} = B\left[\frac{D - n\,a\,\theta_s}{D - B\,n\,a\,\theta_s}\right]$$

$$= B\left[\frac{1}{1 - \dfrac{\dfrac{\phi_2}{100}\,n\,a\,\theta_s}{D - n\,a\,\theta_s}}\right]$$

or with an error of less than 1 per cent

$$\frac{\theta}{\theta_s} = B\left[1 + \frac{\frac{\phi_2}{100}\, n\, a\, \theta_s}{D - n\, a\, \theta_s}\right]$$

which reduces to

$$\frac{\theta}{\theta_s} = \left(1 + \frac{\phi_2}{100}\right)\left[1 + \frac{\frac{\phi_2}{100}\, n\, a\, \theta_s}{234 + \theta_0 + a\, \theta_s\,(1 - n)}\right] \quad \textbf{(15)}$$

While equation (**15**) may be used for calculating the temperature rise for any altitude, it can be greatly simplified (without introducing any large errors) by assuming definite values of θ_0, θ_s, and n. Even though these values vary considerably in practise the effect on the final results is small and the error introduced by using average values is permissible.

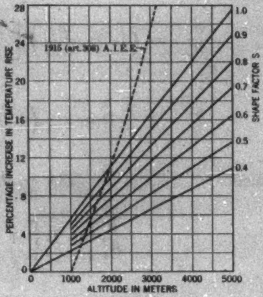

FIG. 7

Asumming a difference in altitude of 3000 m. (9840 ft.) or when $A = 3$ (in equation $\phi_2 = 5\ AS$) $S = 1$, $n = 0.8$, $\theta_0 = 30$ deg. cent. $\theta_s = 50$ deg. cent., and

$a = 0.0$, $\frac{\theta}{\theta_s} = 1.15$ or the new value of $\phi = 5.0\ AS$

$a = 0.5$, " $= 1.164$ " " " " " " $= 5.47\ AS$

$a = 1.0$, " $= 1.1753$ " " " " " " $= 5.85\ AS$

In other words, ϕ the percentage increase in temperature, ranges from 5 AS to 5.85 AS, depending on the ratio of copper loss to total (iron + copper) loss. Then we may put

$\phi = AS\,(5 + 0.85a)$ or with a maximum positive error of only 2.5 per cent when $a = 1$.

$$\phi = AS\,(5 + a) \quad \textbf{(16)}$$

Fig. 7 gives curves plotted from equation (**16**) where $a = 0.5$, and $e = 1$.

Table II shows a comparison between observed temperature rises and calculated temperature rises by equation (**16**) using the data shown in Tables III, IV and V giving complete data on observations conducted at Pittsfield, Boulder and at Leadville.

TABLE NO. II.

Test No.	Average surface rise deg. cent. at Pitts-field	Percentage temperature rise above tests at Pittsfield.					
		Tests at Boulder			Tests at Leadville		
		Predicted by equation (**16**)	Observed above		Predicted by equation (**16**)	Observed above	
			Average room	Idle tank		Average room	Idle tank
				TANK NO. I.			
1	17.5	6.45	6.83	8.32	12.60	10.0	11.0
2	29.7	6.41	5.5	7.0	13.10	13.5	14.6
3	44.4	5.95	6.7	7.5	11.40	12.6	13.3
Mean values.........		6.27	6.34	7.6	12.4	12.0	12.9
Mean value obtained by formula*.....................					11.51		
				TANK NO. II.			
4	15.8	5.00	0	0	9.95	6.06	7.40
5	31.1	5.10	3.3	1.85	10.00	8.75	9.50
6	44.4	4.90	1.95	1.78	9.85	8.65	9.95
Mean values........		5.0	1.42	1.27	9.93	7.82	8.95
Mean value obtained by formula*.....................					9.3		
				TANK NO. III.			
7	9.85	3.42	0	0	6.62	5.77	5.6
8	31.5	3.50	−3.34	− 3.34	6.92	3.82	4.05
9	48.3	3.35	−2.82	− 3.26	6.70	4.32	5.0
Mean values........		3.42	−2.08	− 2.2	6.74	4.6	4.88
Mean value obtained by formula*.....................					6.12		

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*$\phi = 4.86\,A\left(\frac{W_c}{W_c + W_r}\right)$. NOTE: Instead of using here a constant value (S) for $\left(\frac{W_c}{W_c + W_r}\right)$ for different temperature rises, the values for W_c and W_r are based upon actual watts dissipated as given by equations (**1**) and (**10**) for surface temperature rises shown in second column above. Since the values for W_c and W_r change in opposite directions for change in altitude, the calculations are made for the proper values at an altitude of 1525 m. (5000 ft.) above sea level.

TABLE NO. III.

RECORD OF TESTS ON TANK NO. I. (CORRUGATIONS 22.8 CM. IN DEPTH.)

Test	Volts	Amperes	Watts[1] observed by		Temperature in deg. cent.					Observed barometric pressure in mm. Hg.	Calculated altitude in meters above		Humidity of air in % of saturation	Grains of moisture per litre of air	Date of test
			Volts × amp.	Watt-meter	Idle tank	Avg.[2] room	Average maximum oil[3]				Sea-level	Pittsfield			
							Actual	Rise above Idle tank	Rise above Avg. room						
								PITTSFIELD							
1	110	14.35	1565	1564	30.3	30.0	51.1	20.8	21.1	730	360	0	21	0.106	3-27-15
2	110	26.6	2913	2907	30.4	30.1	64.7	34.3	34.6	735	300	0	16	0.080	3-20-15
3	110	43.1	4728	4707	32.4	32.0	82.9	50.5	50.9	727	395	0	17	0.95	3-23-15
								BOULDER							
1	110	14.5	1583	1538	36.0	36.0	58.5	22.5	22.5	615	1880	1520	21	0.132	5-14-15
2	110	26.7	2925	2908	37.3	37.4	74.0	36.5	36.7	620	1810	1510	18	0.130	5-12-15
3	110	43.5	4773	4688	37.2	37.2	91.5	54.3	54.3	621	1795	1400	20	0.140	5-10-15
								LEADVILLE							
1	110	14.35	1565	1564	29.9	29.8	53.0	23.2	23.1	523	3320	2960	25	0.122	7-24-15
2	110	26.4	2891	2897	30.0	30.0	69.3	39.3	39.3	519	3390	3090	20	0.099	7-23-15
3	110	43.1	4728	4727	30.9	30.9	88.2	57.3	57.3	537	3080	2685	22	0.106	7-22-15

(1) Less instrument losses.
(2) Average of 4 thermometers.
(3) Average of 3 thermometers.

TABLE NO. IV.
RECORD OF TESTS ON TANK NO. II. (Corrugations 8.9 cm. in Depth.)

Test	Volts	Amperes	Watts[1] observed by		Temperature in deg. cent.					Observed barometric pressure in mm. Hg.	Calculated altitude in meters above		Humidity of air in % of saturation	Grains of moisture per litre of air	Date of test
			Volts × amp.	Watt-meter	Idle tank	Avg.[2] room	Average maximum oil[3]				Sea-level	Pittsfield			
							Actual	Rise above Idle tank	Rise above Avg. room						
							PITTSFIELD								
4	110	14.25	1554	1547	30.5	30.1	54.9	24.4	24.8	727	395	0	16	0.081	3-19-15
5	110	28.4	3111	3117	32.3	32.0	74.3	42.0	42.3	728	382	0	14	0.081	3-18-15
6	110	41.0	4493	4507	32.4	32.0	88.7	56.3	56.7	723	443	0	14.5	0.078	3-16-15
							BOULDER								
4	110	14.25	1554	1556	31.5	31.1	55.9	24.4	24.8	616	1890	1495	34	0.176	5-20-15
5	110	28.8	3163	3117	36.4	35.5	79.2	42.8	43.7	613	1910	1528	29	0.188	5-18-15
6	110	41.5	4552	4573	38.8	38.3	96.1	57.3	57.8	613	1910	1467	22.5	0.162	5-17-15
							LEADVILLE								
4	110	14.1	1548	1547	30.2	30.0	56.4	26.2	26.4	520	3370	2975	21	0.110	7-27-15
5	110	28.4	3111	3117	31.8	32.0	78.0	46.2	46.0	519	3390	3008	24	0.130	7-26-15
6	110	41.3	4517	4517	31.7	32.0	93.6	61.9	61.6	519	3390	2947	24	0.116	7-25-15

(1) Less instrument losses.
(2) Average of four thermometers.
(3) Average of three thermometers.

TABLE NO. V.

RECORD OF TESTS ON TANK NO. III. (PLAIN)

Test	Volts	Amperes	Watts[1] observed by		Temperature in deg. cent.					Observed barometric pressure in mm. Hg.	Calculated altitude in meters above		Humidity of air in % of saturation	Grains of moisture per litre of air	Date of test
							Average maximum oil[3]								
								Rise above							
			Volts × amp.	Watt-meter	Idle tank	Avg.[2] room	Actual	Idle tank tank	Avg. room		Sea-level	Pittsfield			
							Pittsfield								
7	110	3.28	348	347	29.4	29.9	45.5	16.1	15.6	732	333	0	18	0.092	3- 2-15
8	110	9.78	1063	1066	30.1	30.2	72.1	42.0	41.9	743	201	0	17	0.092	3- 4-15
9	110	15.2	1658	1657	30.4	30.1	90.3	59.9	60.2	736	285	0	18	0.092	3- 6-15
							Boulder								
7	110	3.23	354	342	33.6	33.6	49.0	15.4	15.4	616	1890	1557	40	0.240	5-25-15
8	110	9.87	1073	1067	33.9	33.9	74.4	40.5	40.5	613	1910	1609	24	0.148	5-23-15
9	110	15.6	1703	1637	33.7	33.2	91.7	58.0	58.5	619	1825	1540	32	0.190	5-22-15
							Leadville								
7	110	3.26	346	313	29.5	30.0	46.5	17.0	16.5	519	3390	3057	18	0.105	7-29-15
8	110	3.78	1063	1066	29.8	30.0	73.5	43.7	43.5	519	3390	3189	19	0.113	7-28-15
9	110	15.2	1658	1667	30.0	30.1	92.9	62.9	62.8	520	3370	3085	19	0.105	7-27-15

(1) Less instrument losses.

(2) Average of four thermometers.

(3) Average of three thermometers.

An inspection of Table II shows that the calculated and observed temperature rises for all tests on tank No. I, which is the most important of the three, (because the effect is greatest) agree very well. Also there is only a slight difference, the observed being lower than the calculated values, for the Leadville tests on tanks No. II and III. Why the observed and calculated values for the Boulder tests on Tanks No. II and III do not agree any better is not clearly understood. This difference may be partly explained by the fact that different instruments were used at Boulder than at Pittsfield. A small error in watts would be expected to be more apparent for the smaller tanks where the loss is small. Another and probably better reason for this difference is that the room temperatures were from three to six degrees higher at Boulder than at Pittsfield, which as seen before, has the effect of increasing the tank's effectiveness for radiation. The difference is largest for the plain tank where radiation plays the more prominent part. Also the humidity of the air at the former place was somewhat higher, but in general this has been shown to have very little effect. (See TRANS. A. I. E. E. 1913, Vol. XXXII, Part I, p. 235. Frank and Dwyer)

EXPERIMENTAL OBSERVATIONS

Observations were made under exactly the same conditions, with the above exceptions, at

Pittsfield, Mass. approx. 305 m. (1000 ft.) above sea level
Boulder, Colo.* " 1830 m. (6000 ft.) " " "
Leadville, Colo. " 3360 m. (11,000 ft.) " " "

The writer had charge of the observations at Pittsfield and at Leadville. This eliminates the personal element which is usually important in any test on heating.

The housing (Fig 8) consisted of pressboard walls made up into sections so it could be easily assembled and disassembled. A view of the arrangements on the inside of the housing is shown in Fig. 4. The room temperature was controlled by means of sliding covers. In a few instances when the supplied loss was small, in order to keep the room temperature from falling below the chosen value, it was necessary to use a small electric heater.

Two 40.6-cm. (16-in.) desk fans were operated in a vertical position in opposite corners of the room, with pressboard screens placed between the fans and the tank to prevent breezes from striking the surface of the tank. Tests made in this manner at different outside temperatures showed that under all conditions the difference in air temperature (approx. 90 cm. from tank surface) on level with the top and bottom of tank did not in any case exceed 2 deg. cent., whereas without the fans sometimes as much as 6 to 8 deg. cent. difference was observed. The room temperature used as a base was taken as the average of the four thermometers placed on a level with the center of the tank, in each corner of the room as shown in Fig. 4. In addition to the room temperature being used as the base, the temperature of a small lighting size transformer tank, filled with oil, set with its center on a level with the center of the tank under test, was also used. This was subjected less to quick changes in the outside air, than was the internal room temperature. The percentage of humidity of the air, during all tests, was determined by means of wet and dry mercury bulb thermometers. The barometric pressure was observed with a mercurial barometer.

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*It is desired here to acknowledge indebtedness to Prof. H. S. Evans, of the University of Colorado, who had charge of and conducted the observation at Boulder at the expense of the University Eng. Dept. Also the writer wishes to ackdowledge the excellent work done by Messrs. C. D. Fawcett and T. M. Victory in carrying on the observations at Boulder and at Leadville.

Tanks. The dimensions of the three tanks used are given in Fig. 1.

It will be noted from the illustrations that the covers for the three tanks are insulated thermally from the tanks proper. Also for tank No. 1 the two plain sides were covered each with two thicknesses of 2.54-cm. (1-in.) hair felt, so as to make the loss by convection a maximum. However, in order to determine the amount of heat passing out through these blanketed sides, the blanketing material was covered with a sheet iron casing of black color. By observing the temperature of this casing and also of the covers it was possible to determine the amount of heat lost by these insulated areas.

Tank No.	Run No.	Estimated loss by blanketed areas in percentage of of input loss
I	1	2.5
	2	2.2
	3	2.0
II	4	1.32
	5	0.75
	6	0.70
III	7	1.5
	8	1.8
	9	1.9

The foregoing tabulation gives the estimated loss by these blanketed areas in percentage of input loss on each tank for the tests conducted at Pittsfield.

We can therefore neglect these surfaces in giving the ratio of developed (effective for convection) to envelope (effective for radiation) surfaces. However, in making calculations of dissipated heat, these blanketed areas have been considered.

The developed surfaces effective for convection therefore were as follows:

Tank No. I. (24 corr. 22.9 cm. in depth)		
Corr.—24×48.5×141.5	165,000 sq. cm.	(25,600 sq. in.)
Space above corr. not blanketed	3,225 "	(500 ")
	168,225 "	(26,100 ")
Tank No. II. (43 corr. 8.9 cm. in depth.)		
Corr.—43×19.8×130	111,000 sq. cm.	(17,200 sq. in.)
Plain bands at top and bottom 40.6 (73.8+π×63)	10,980 "	(1,700 ")
	121,980 "	(18,900 ")
Tank No. III. (Plain sides)		
59×π×130	24,200 "	(3,750 ")

The envelope surfaces (not blanketed) effective for radiation were:

Tank No. I. 24×6.02×159	23,000 sq. cm.	(3,560 sq. in.)
Tank No. II. 167.5 (4×18.4+π×63)	45,500 "	(70,600 ")
Tank No. III. 59×π×130	24,200 "	(3,750 ")

The values of S as defined in equation (**14**) for the above tanks are:

Tank No.	S
I	0.85
II	0.67
III	0.435

Method of Loading. Each tank was fitted with tubes wound (non-inductively) with resistance wires of zero temperature coefficient, and so arranged that by connecting in parallel various combinations proper losses were supplied, at 110 volts pressure, to give three maximum oil rises ranging from about 20 to 60 deg. cent. These tubes were so grouped that for each test the loss was uniformly distributed over the tank. By means of a diagrammatic record the same grouping was used at Pittsfield, at Boulder and at Leadville. The tubes were supplied at Pittsfield and at Boulder with current from an a-c. generator, and from an a-c. circuit of the Colorado Power Company at Leadville. The regulation was within one per cent under all conditions. In fact, at Leadville the regulation was considerably better than one per cent.

The instruments consisted of

One 150-volt voltmeter
One 5-ampere ammeter
One 600-watt, 15-ampere, 150-volt wattmeter
One 10:1 ratio current transformer.

The wattmeter was used to obtain a check on the input losses as found by the volt-ammeter method. (volts × amperes). The same instruments were used at both Pittsfield and Leadville. At Boulder the meters were furnished by the University of Colorado. All the thermometers were of the mercury bulb type and only those reading accurately within ½ deg. cent. by calibration were used. The four used for room read in ⅕ deg. divisions. The three used for the maximum (top) oil read in ½ deg. divisions.

In order to obtain the temperature gradient along the surface of the tanks (for checking input against dissipated losses), thermometers were placed at short intervals from top to bottom on both outside and inside bend of corrugations. Small felt pads and putty were placed over the bulbs to protect them from the influence of the room. At Pittsfield thermocouples were welded to the tank surface adjoining five of these thermometer bulbs to obtain a check on the temperatures. The thermocouples and thermometers read together, in almost all cases, within 1 deg. cent., showing that the felt pads were not causing hot spots from a blanketing effect.

For each test the run was continued at least 8 or 10 and in some cases 15 to 20 hours after conditions became constant, and an average of these readings (observed hourly) was taken as the final value.

CONCLUSIONS

The present A. I. E. E. recommendation (§308) reads as follows:

> Altitude. Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which the machine is intended to work in ordinary service, this height is assumed not to exceed 1000 meters (3300 ft.). For machinery operating at an altitude of 1000 meters or less, a test at any altitude less than 1000 meters is satisfactory, and no correction shall be applied to the observed temperatures. Machines intended for operation at higher altitudes shall be regarded as special. See Para. 267. It is recommended that when a machine is intended for service at

altitudes above 1000 meters (3300 ft.) the permissible temperature rise at sea level, until more nearly accurate information is available, shall be reduced by 1 per cent for each 100 meters (330 ft.) by which the altitude exceeds 1000 meters. Water-cooled oil transformers are exempt from this reduction.

COMPARISON OF A. I. E. E. RECOMMENDATIONS WITH $\phi = AS\ (5 + a)$

	Per cent increase in temperature rise above temperature rise at sea level.				
Altitude above sea level — Meters.	1000	2000	3000	4000	5000
Altitude above sea level — Feet....	3280	6560	9840	13,120	16,440
A. I. E. E. (§308)......	0	11.1	25.0	42.8	66.8
Shape factor S	$\phi = 5.5\ AS$				
1.0	5.5	11.0	16.5	22.0	27.5
0.75	4.12	8.25	12.4	16.5	20.6
0.435	2.39	4.78	7.18	9.57	12.0

The above indicates that for equal iron and copper losses the present A. I. E. E. recommendations are for a difference of altitude of 3000 m. (9840 ft.), about 1.5 times too high for a surface with no radiation; about two times too high, for a surface dissipating 75 per cent of its loss by convection and 25 per cent by radiation (which ratio corresponds somewhat more nearly to surfaces of simple corrugations); and about 3.5 times too high for a plain surface ($S = 0.435$). For altitude differences greater than 3000 m. the error is larger, while for altitude differences less than 3000 m. the error is less.

Recommendations. It is recommended that for self-cooled (oil-immersed and natural draft) transformer, either the formula $\phi = AS\ (5 + a)$ or the one simplified and shown below be adopted and that no correction be made when $A = 1$ or less. If we assume that $e = 1$ and that the ratio of copper to iron loss is 3:2 respectively and divide the numerator and denominator of the expression for the shape factor through by "developed surface," we have

$$\phi = \frac{A\ (5 + 0.6)}{1 + 1.3\,\dfrac{\text{envelope surf.}}{\text{developed surf.}}}$$

or

$$\phi = \frac{5.6\ A}{1 + 1.3\ R} \qquad (17)$$

where R = area of envelope cooling surface divided by area of developed cooling surface.

NOTE: In practise R varies from 1.0 (plain surface) to approximately 0.125 (complicated surface). For natural draft transformers dissipating all heat by convection $R = 0$.

Example. Let it be required to determine the temperature rise that a transformer in tank No. II (corrugations 8.9 cm. in depth) giving a 45 deg. cent. rise at sea level will attain when taken to an elevation of 3000 m. (9840 ft.).

We have $A = 3$

and

$$R = \frac{46080}{121980} = 0.378$$

Then

$$\phi = \frac{5.6 \times 3}{1 + 1.3 \times 0.378} = 12.8 \text{ per cent}^*$$

or temperature rise at 3000 m. above sea level will be 45 deg. $+ \left(\frac{12.8}{100}\right)$ 45 deg. = 50.7 deg. cent.

If it is desired to make correction in the opposite direction, *i.e.*, one of reduction instead of one of addition, and if we let ϕ_r = percentage reduction in temperature rise at the high altitude

$$\phi_r = \frac{100\,\phi}{100 + \phi} \qquad (18)$$

$$= 11.44 \text{ per cent or}$$

temperature rise at sea level will be, 50.7 deg. $- \left(\frac{11.44}{100}\right)$ 50.7 deg. = 45 deg. cent.

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[*] It should be noted that this percentage increase applies to the max. oil temperature rise rather than to the average temperature rise of the windings, which in some cases differs considerably from the oil. Since the difference between the winding and max. oil temperatures should be about the same at all altitudes, the same number of degrees correction should be made for the windings as for the oil.

DISCUSSION ON "EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED STATIONARY INDUCTION APPARATUS" (MONTSINGER), CLEVELAND, OHIO, JUNE 27, 1916.

R. W. Sorensen: Mr. Montsinger in presenting this most excellent treatise has placed before us a second set of data* for the purpose of enabling our Standards Committee to construct an accurate ruling, whereby the effect of altitude upon the heating of electrical apparatus may be determined.

In classing this as a second set of data, I have used that given by Frank and Dwyer as the first set, because in both these instances the test data used in arriving at the conclusions given, were derived from tests made largely at the same geographical locations; and also because the working up of these data was accomplished by the use of the same formulas of Dr. Langmuir's and others, as may be seen from a comparison of the paper by Mr. Montsinger with that previously published by Messrs. Frank and Dwyer.

Unfortunately, the results of the two investigations do not check as closely as would be desirable, as will be seen by the curves of Fig. 2. Also the curves obtained from these results do not approximate the A. I. E. E. rules (§308), as has already been pointed out by Mr. Montsinger in his paper.

For our assistance, therefore, I should like to present data of a series of heat run tests that I made on two oil-insulated self-cooled transformers. These tests were made at Schenectady, New York, Pittsfield, Mass., Grand Junction, Colorado, and Leadville, Colorado, with altitudes of 75, 345, 1525 and 3190 meters respectively, as indicated by barometer readings at the time and place of test.

The transformers used for the tests were rated 60-cycle, 125-kv-a., 11,000 volts to 2300 volts, and contained approximately 1300 pounds of active material (copper and iron). They were inclosed in corrugated sheet steel tanks with a cast iron base and wrought iron straps at the top for holding the corrugations in place. Each tank was about 5½ feet high, and occupied a floor space of approximately two feet by three feet in area.

The tests which I made, while not conducted in a special portable room, as were those of Mr. Montsinger, were conducted with special care as to uniformity of ventilation conditions in the large rooms of the factories and power plants where the tests were made. Observations were made of humidity at each place of test, and agreement of conditions in this respect found to be such that no corrections for differences of humidity were necessary.

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*Frank and Dwyer "The Temperature Rise of Stationary Induction Apparatus as Influenced by the Effects of Temperature, Barometric Pressure and Humidity of the Cooling Mediums," page 235, A. I. E. E. TRANSACTIONS, Vol. XXXII.

All heat runs were conducted by the standard motor generator method of loading two transformers for heat run, and readings of currents, volts and watts input to each transformer were made, to insure the accuracy of the knowledge of the watts to be dissipated, regardless of variations in wave form of voltage supply, etc.

The results of these tests were as follows:

Place.	Actual watts loss.	Rise in oil deg. cent.	Rise in oil deg. cent. reduced to same loss 4820 watts
Schenectady	4820	36.0	36.0
Pittsfield	4820	37.5	37.5
Grand Junction	3965	32.5	38.9
Leadville	4570	39.6	41.8

From these results there is plotted on Fig. 1, curve *A* showing the probable change in temperature rise at various altitudes for a constant loss of 4820 watts in the transformers. The points located on the figure show the actual conditions as found by the tests made. Considering curve *A* on Fig. 1 as indicative of the true condition, it has been replotted as curve *D*, Fig. 2. Assuming, however, the test at Schenectady (36 deg. cent. rise) as correct and using this as a base, a greater influence of altitude is shown when the temperature rise of Leadville is compared with it and there results curve *E*, which has been plotted in Fig. 2, because it shows this condition, and also because it gives a possible conservative rule easy to follow, its slope being such as to show ½ of 1 per cent increase in temperature rise for each 100 meters altitude.

Applying to results of tests on these transformers Mr. Montsinger's method of analysis, we find the tanks were similar to those of Fig. 1. tank No. 2 in his paper, except in that the corrugations were spaced a greater distance apart. The tank dimensions were 65 inches (165 cm.) high over all, and had thirty-two 3½ in. (8.9 cm.) corrugations each, with a pitch of three inches (7.62 cm.) per corrugation, making the developed surface as follows:

*Corrugations	4×66.5×55	14,630 sq.in. (94,500 sq.cm.)
Upper plain band	4(29+24.75″)	426 “ “ (2750 “ “)
Lower plain band	6(29+24.75″)	640 “ “ (4130 “ “)
Envelope surface	= 65(29 − 24.75″) =	6950 sq. in. (44,800 sq. cm.)
		15,696 sq. in. (101,330 sq. cm.)

Therefore:

$$\text{(Leadville)} = \frac{5.6 \times 3.19}{1 + 1.3\,(6950/15696)} = 11.3 \text{ per cent.}$$

---

*66.5 inches is the developed length of each one of four sheets of steel, making up the corrugated walls of the tank, At first sight this result does not appear to check very closely the tests made upon the 125-kv-a. transformers as will be seen by comparing curves *D* and *E* with curve *C* of Fig. 2. A very careful consideration, however, of the data obtained from the tests on the transformers shows a possibility of a very close agreement between these and the results obtained by Mr. Montsinger.

At the time the tests were made on these transformers, it was feared that in moving about from place to place it would not be possible to have a fixed set of conditions at each place, and consequently a number of heat runs at different loads and voltages were made at Pittsfield (altitude 345 meters). These many tests, carefully made and checked with each other make them worthy of consideration in establishing a basic "rise of temperature."

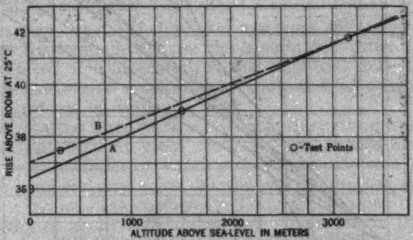

FIG. 1—TEMPERATURE RISE OF 125-KW., 11000-2300-VOLT TRANSFORMERS DUE TO CHANGE IN ALTITUDE.

CURVE A—PROBABLE TEMPERATURE RISE CURVE FOR 125-KV-A. TRANSFORMERS AS OBTAINED FROM ALL FOUR TEST POINTS

CURVE B—PROBABLE TEMPERATURE RISE CURVE FOR 125-KV-A. TRANSFORMERS AS OBTAINED WITH TESTS AT PITTSFIELD AS BASIC

With the temperature rise for a loss of 4820 watts determined at Pittsfield as a base, the possible temperature increase curve may be drawn through the Pittsfield and Leadville points as of curve *B*, Fig. 1. This curve shows a rise of 37.5 deg. at sea level, which means an increase in temperature rise of approximately 1.2 per cent at Pittsfield over that of Schenectady.

By Mr. Montsinger's formula:

$$\phi \text{ (Pittsfield)} = \frac{5.6 \times 0.345}{1 - 1.3\ (6950/15696)} = 1.22 \text{ per cent.}$$

With probable rise of 37.05 deg. cent. at sea level (Schenectady) and a rise of 41.8 deg. cent, at Leadville, there is an increase in temperature rise at Leadville over that at Schenectady (sea level) of 4.75 deg. cent. or 12.8 per cent, which compares favorably with the increase of 11.3 per cent as obtained by the use of Mr. Montsinger's equation (17), and we can draw curve *K* as a possible curve for the 125-kv-a. transformers as of the tests made in June, 1910.

It is quite probable, therefore, that the curve *E* is somewhat high, and that practically all self-cooled oil-insulated transformers would give results within the range limited by curves *C* and *D*.

These facts show very clearly that Mr. Montsinger's paper has advanced us materially in the solution of this problem, but it seems hardly advisable for the following reasons, to adopt the recommendation as given in his paper whereby his equation (17) is to be used. His Fig. 7 shows that for a shape factor of 0.9, a curve that practically coincides with curve *E*, Fig. 2. Also it is possible that there may be conditions governing the oil circulation of actual transformers different from those of the experimental apparatus used by Mr. Montsinger in obtaining his results, so that some curve between curves *E* and *C* of Fig. 2

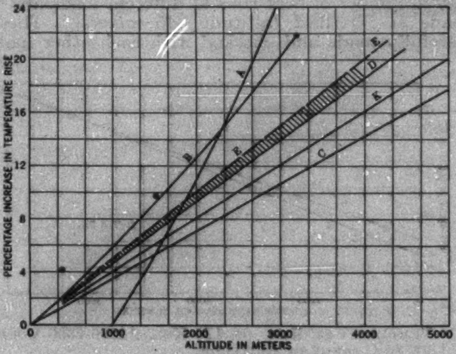

FIG. 2

CURVE A—1915 (ART. 308) A. I. E. E. RULES

CURVE B—FROM TABLE II D, FRANK & DWYER, PAGE 254, A. I. E. E. TRANSACTIONS, VOL. XXXII

CURVE C—VALUES FOR 125-KV-A. TRANSFORMERS OBTAINED BY EQUATION (17), MONTSINGER, A. I. E. E. PROCEEDINGS, APRIL, 1916.

CURVE D—VALUES FOR 125-KV-A. TRANSFORMERS OBTAINED FROM TESTS, AS OF CURVE A, FIG. 1

CURVE E—FOR SUGGESTED RULE OF ONE-HALF OF ONE PER CENT INCREASE FOR EACH 100 METERS ALTITUDE

CURVE K—VALUES FOR 125-KV-A. TRANSFORMERS WITH THE TESTS AT PITTSFIELD BASIC, AS OF CURVE B, FIG. 1

would more nearly approach the average results of a large number of transformers of various designs.

I would recommend, therefore, that, until further information can be obtained, an increase of temperature of one-half per cent be allowed for each 100 meters altitude, as this will be more nearly correct than the present rule and will at the same time allow ample margin for safety, as the ½ per cent is undoubtedly somewhat in excess of the necessary allowance.

A. I. E. E. rule § 308 would then read the same as at present with the exception of the next to the last sentence which would read about as follows:

It is recommended that when a machine is intended for service at altitudes above 1000 meters (3300 feet) the rise in temperature shall be determined, until more nearly accurate information is available, by adding to the rise at sea level one-half per cent for each 100 meters (330 ft.) of altitude.

Alexander Gray: If duplicate machines are tested by different men for temperature rise the results will differ. Accurate measurement of temperature is not easy and any small error in reading will give results from which it will be impossible to deduce any law of cooling.

I once started some work on the heat dissipation from vertical surfaces but without great success. The apparatus consisted of a wooden cylinder on which strip copper was wound and the surface temperatures were determined by resistance measurements. By juggling coefficients I finally obtained a radiation coefficient of about 0.75 and a law of convection that agreed accurately with Lorenz law. I am inclined to think, however, that I was looking for such a law and adjusted the radiation coefficient to suit and, having come to that conclusion, I decided thereafter to leave the subject to the physicist.

There has recently been developed at the Bureau of Standards an instrument by means of which the actual radiation from a surface may be determined so that the field looks promising for those interested in heating problems.

It is of interest to note that in the report presented by the Transmission Committee, the Trinidad Company states that, at high altitudes, transformers ran ten per cent hotter than normal while rotating machines ran only five per cent hotter and yet the rotating machine is that in which nearly all the heat is dissipated by convection.

When heat is dissipated by means of air blown over a surface a reduction of the density of the air causes an increase in its temperature but this does not necessarily mean that the surface temperature is increased by the same amount. There is a large temperature gradient between the surface and the air about which we know very little and because of this I do not believe that we are in a position to make any recommendation as to the correction to be made for barometric pressure.

Experimental data such as those contained in Mr. Montsinger's paper add to our knowledge of a very difficult subject but I believe much more of such work is necessary before we are in a position to make more than a recommendation as to the correction for barometric pressure.

V. M. Montsinger: In reference to Prof. Sorensen's discussion, although the curve which he considers most reliable checks very closely the results I obtained, he does not recommend a correction in accordance with the formula, but recommends one correction for all transformers, which is slightly less than the maximum correction by the formula. He states that it will take care of all the cases which come up. That is true. My point is, however, and I have tried to emphasize it, if we have only one correction factor for all types and have one transformer for which the correction is only about 7 per cent as is the case for a tank having plain surfaces, for a difference of 10,000 ft. in elevation, it is not necessary to design this transformer with a margin of 15 or 20 per cent. I believe that it is advisable to adopt some formula that will take care of this difference, because if we attempt to continue to make one correction for all types of apparatus, especially for stationary and moving types, the problem will still remain in a very unsettled condition.

Regarding Prof. Sorensen's statement that the conditions may not have been the same, where I heated the tanks by means of resistance tubes, as are the conditions in an actual transformer. This may be true if we considered only the windings of the transformer and depended on them (or the resistance tubes) for comparative temperatures. Due to the uncertainties of obtaining accurate resistance measurements, the top or maximum oil is usually, for comparative purposes, the better criterion. This has been used altogether in comparing observed with calculated values. In order then that this means of heating the tanks affect the accuracy of the readings as compared with an actual transformer, it would be necessary that the temperature gradient of the oil, as affected by barometric pressure, change more under the one condition than under the other condition. There does not seem to be any logical reason why this should be the case.

I agree with Mr. Gray that it is very hard to obtain an accurate law covering the effect of barometric pressure on heating, because in practise this correction is usually small and there are always errors which are liable to creep in. For that reason I do not think we should base any conclusions on, say one test. For my observations, there were three different tests made on each style of tank. An examination of the tabulation of the results will show that although the tests vary slightly, which is to be expected, there are no large variations. This would indicate that the method of making the tests was considerably more accurate than the method usually used in practise.

It is under any condition, a difficult matter to separate radiation from convection, but the law for radiation has been fairly definitely settled and convection follows somewhat the same law, but for smooth surfaces the problem is not as difficult as it would be if we attempted to separate the losses from moving machinery. For the latter condition, the surfaces are more irregular and we do not know the laws, as a whole, under which the heat is thrown out from the machine into the air.

Presented at the 33d Annual Convention of
the American Institute of Electrical Engineers,
Cleveland, O., June 27, 1916.

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THE RESTORATION OF SERVICE AFTER A NECESSARY INTERRUPTION

BY F. E. RICKETTS

ABSTRACT OF PAPER

Since electricity has become recognized as the most important means for transmitting energy the value of uniformity in voltage and frequency has become more and more apparent. The phenomenal growth during the last few years in the electrical industry has been due as much to the marked advances in the methods for maintaining a uniform service as to any other cause. During this period of rapid development many papers have been written, setting forth different ideas as to ways of providing against interruptions. At the beginning, these ideas varied greatly, but now there seems to be some hope for a more uniform practise as to this type of apparatus.

In writing this paper I have assumed that the field has been pretty well covered so far as the prevention of interruptions goes, but have to call attention to that class of interruptions which so far have been and will likely continue to be unavoidable; and have endeavored to describe certain means whereby the effect of unavoidable interruptions may be reduced to a minimum.

GENERALLY speaking, alternating-current generators cannot be injured by overloading for a few minutes, and since the sudden interrupting of a circuit carrying heavy currents tends to produce abnormal voltages it is very advisable during abnormal conditions on an electrical system to keep all the switches closed except when the opening of a switch or switches is necessary in order to disconnect some section of the system that has become permanently disabled. Especially is this true when we consider the delay usually experienced in restoring service on a portion of a system that has been temporarily cut out, even though there may have been no trouble on that portion.

Since the amount of service affected by the opening of a switch is in proportion to the nearness of the switch to the generator, the importance of keeping the switches closed increases as we approach the generators; consequently the generator switches should be arranged so that they will never open due to any overload, however great the current may be. But for the chance of trouble within the generators themselves, the switches controlling them would be better made non-automatic; however, with such an arrangement, in case a short circuit or a ground should occur within the generator, the service would be seriously disturbed until the operator could open the switch by hand, and there would also be a possibility of the generator being seriously damaged if not destroyed.

Fig. 1 illustrates an ideal scheme for the protection of generators. The generator is three phase, but in describing the scheme we need only consider a single phase as the action of the others will be the same. At each extremity of phase *A* there is a current transformer, transformer *A*1 being near the oil switch and transformer *A*2 being in this case near the neutral, so that any current passing completely through phase *A* will produce in the secondaries of the two transformers, currents that are exactly equal and in phase, the transformers having equal ratios and connected so that their secondaries will work in series with their instantaneous voltages in the same direction. Then if a relay such as *A*3 is connected with its actuating coil between the two wires connecting the transformers, and its contact circuits connected to both the trip coil of the switch in the armature circuit and the trip coil of the switch in the field circuit, the terminals of the actuating coil of the relay will always be at the same potential as long as there is no leakage of current in the winding of phase *A*, regardless of the load on the generator or whether it is operating as a generator or motor. Therefore, as long as there is no trouble in the generator, no current will flow through the coil of the relay and there will be no tendency to trip the switch,

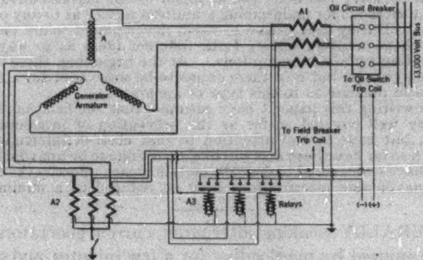

FIG. 1—CONNECTIONS FOR RELAYS ON GENERATORS

but just as soon as current starts to leak from phase *A* to one of the other phases or to ground, there will be a difference in the value of the current flowing through the two transformers, which difference will be represented by a current in the secondary of one transformer, but not in the other; therefore this unbalance in the secondaries will have to flow through the actuating coil of the relay which will cause its contacts to close and instantly open both the armature circuit and the field circuit, thereby not only preventing current from feeding from the bus into the damaged generator, but also preventing the damage that would have been caused by current generated by this generator had the field circuit remained closed.

Now, that we have the generator switches arranged so that they will not open on overload, so long as the generator is in working condition and the other switches on the system assumed to be equipped for selective operation, let us consider what would happen if, when an arc occurs between two conductors of the system at a point where the insulation will not be permanently impaired we simultaneously interrupt the field circuits of all the generators for a short interval of time; say, one or two seconds. When the field circuits of the generators are opened, the voltage of the system will very quickly drop to near zero, especially is this true when the short circuit is severe, in which case the heavy armature current will tend to demagnetize the generators, even before the field circuits are opened. This drop in voltage will be much more rapid than could be accomplished by reducing the voltage applied to the field circuits while the field circuits remain closed since then, as the magnetism of the fields decrease there would be induced in the closed field circuit a voltage that would oppose the decrease in field current. Figs. 2 and 3 give a comparison of the relative time required for the armature voltage to die out when the generator field is opened and when the exciter field is opened. Fig. 2 is for opening of the generator field and Fig. 3 for the opening of the exciter field. If the exciter voltage were lowered by cutting resistance in the exciter field, the time would be still longer. By the time the fields close the arc will have ceased, and as the current builds up in the fields the armature voltage will rise gradually from zero to normal, with total absence of voltage surges and an armature current not exceeding 200 per cent normal. As the armature voltage rises to normal, the service on the entire system will be restored. However, to accomplish the best results, special arrangements of relays should be provided, and when there are synchronous motors on the system, special features should be incorporated in their design.

To assist in the detail description of this system in practise, Fig. 4 is shown, which for practical purposes illustrates the system as it has been successfully used by the Consolidated Gas, Electric Light and Power Company, of Baltimore, for the past three years. A motor *M* is connected through a train of gears to a dial switch *A* in such a way that when the motor is in operation the dial makes one complete revolution in one minute which is the time required for one cycle of operation of the system. The motor is set in operation in response to either of the relays, 1, 2 or 3 which are connected to current transformers in the armature leads of at least one generator that is in operation on the system to be protected. These relays are connected to transformers in the generator leads rather than in any other part of the system for the reason that they will then always be subjected to the same current during a short circuit regardless of the number of generators in service, whereas, if they were placed in the outgoing circuits they would, during a short circuit, be subjected to a current that would be in proportion to the number of generators in service at the time. The action of the relays to start the motor is delayed by a definite-time-limit relay 4 for two seconds in order or give certain of the selective relays

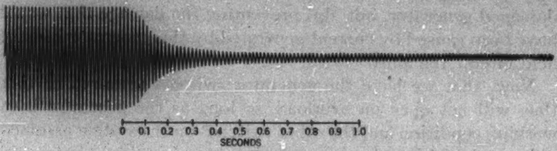

FIG. 2

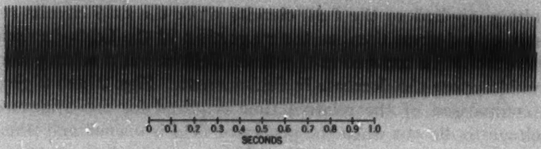

FIG. 3

on the system time to operate or cut out a minor circuit that may be short-circuited, but this time must be less than that required to operate the relays controlling the major part of the system. Very soon after the time-limit relay has caused relay *R*1 to pick up and start the motor, segment *B* which is carried by the rotating dial will touch a contact which will apply current to relay *R*1 during one complete revolution of the dial independent of the time-limit relay. This prevents the motor from stopping after it has once started until it has completed one cycle. Immediately after *R*1 is locked a button on the dial touches a contact that closes relay *R*2, which trips out all the field switches, and about two seconds later another button on the dial touches a contact that closes relay *R*3 which closes all the field switches. The voltage regulator will boost the exciter voltage to a maximum, while the fields are opened so that when the fields are closed the field current will build up to a maximum which is very desirable, as the time required for the generators to pull in step varies inversely as the strength of the field currents. However, when the generators pull in step the voltage may rise so rapidly that the regulator will not be able to control it, therefore, to prevent the voltage from rising too rapidly and overshooting, the relays, *R*4, *R*5 and *R*6 are controlled by the segments near the center of the dial so that during the first one-third cycle of opera-

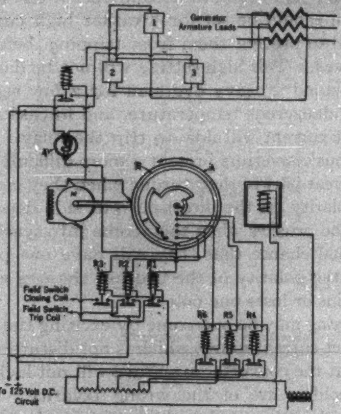

FIG. 4

tion, one-half the resistance in series with the voltage-regulating coil of the regulator will be short-circuited and the resistance will be cut in circuit in steps as the dial rotates, all of the resistance being in circuit at the end of the cycle.

Therefore, since the regulator operates to maintain a constant current in the voltage coil, the voltage will be maintained in proportion to the resistance in the circuit of the voltage coil; that is, the voltage will be restored to normal gradually, which is of great importance in pulling the motors on the system into synchronism.

During the operation of the device, the induction motors will slow down and come back to normal speed, but the relays controlling them should be set for a rather high current, say 400 per cent load to prevent them from tripping before the motors are up to speed. This high setting will not be dangerous as the motors will stand a heavy overload for a few seconds without heating to a dangerous temperature, and in case a motor burns out sufficient current will flow to trip the relay.

Synchronous converters present a more difficult problem since they lose a great part of their torque when they get out of phase, and their polarity on the direct-current side depends upon the polarity of the brushes when they come into synchronism, there being an equal chance that they will have one polarity or the other, since the polarity of the brushes changes every time the armature gains or loses one pole.

This reversing may be overcome by exciting the fields from an external direct-current source which is not disturbed by the short circuit so that the converter armature will not lock in step when the brush holders are of the wrong polarity. This separate excitation need not be equal to that at which the rotary normally operates; in fact, it should not be of full value as it may cause the converters to flash at the brushes as they are pulling into synchronism. In most cases 25 per cent full value of field current will insure the polarity being correct. Fig. 5 illustrates one method that has been successfully used to accomplish the above result. A converter 1 is connected to the positive and negative buses through automatic circuit breakers and has its neutral grounded. There is also a storage battery 2 connected to the buses to take the load during short interruptions on the alternating-current system. When the fields of the generators open and the voltage decreases, current will flow from the battery into the converter until the breakers open. Then, since the voltage of the rotary is not sufficient to hold up the relay *R*1, the plunger of this relay will drop, opening its own circuit and closing that of relay *R*2 which connects the negative bus to a point between the field coils and the rheostat, so that current will flow from the ground through the transformers to the armature and thence through the field coils and rheostat in multiple to the negative bus, the voltage impressed on the field coils being half normal and in the direction to give the proper polarity at the brushes. Therefore, when the converter comes up to speed it will be ready for service.

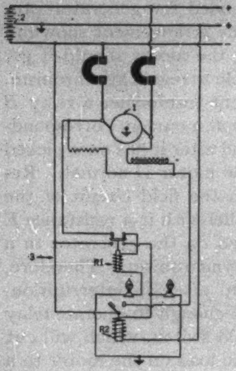

FIG. 5

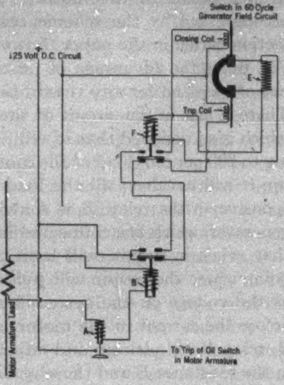
Switch in 60 Cycle Generator Field Circuit
Closing Coil
125 Volt D.C. Circuit
E
Trip Coil
F
25 Cycle Transformer
Motor Armature Lead
B
A
To Trip of Oil Switch in Motor Armature

FIG. 6

Generators	Resistance	Capacity
5000 kv.a.	0.5 ohm	150 amp.
3000 "	1 "	75 "
1000 kw.	2 "	50 "

When no battery is used on the bus, a small battery capable of furnishing the field current should be connected between the neutral and wire marked 3 which would then not be connected to the negative bus. In order to prevent the relays controlling the a-c. side of the converter from tripping while the converter is out of synchronism, they should be set for about 400 per cent normal load.

With synchronous motors the problem is more difficult, since they lose a part of their torque as soon as they get out of synchronism. In this case it becomes necessary to reduce the load to a point where the motor will pull in step. One method of accomplishing this is shown in Fig. 6 which illustrates the connections for reducing the load on a motor-generator until the motor can pull in. A single armature lead is shown, as the connections to the others are similar. In this armature lead is a current transformer which furnishes current to two relays one of which *A* is connected to trip the main switch controlling the motor, is set for 400 per cent load and should have an inverse-time characteristic such that it will trip in about one-third of a second at the maximum current the motor will feed into a short circuit; then it will not trip under heavy load or when a short circuit occurs on the system, but will act very quickly when trouble occurs in the motor. This protection could also be accomplished by the scheme recommended for generator protection earlier in the paper; however, the arrangement shown in Fig. 6 has the advantage of protecting the motor should it get out of step and for any reason be unable to regain synchronism. There is also in the circuit of the current tranformer a relay *B* which is so designed that it will pick up at a current corresponding to 200 per cent load of the motor, and after it has once picked up, it will not drop till the load on the motor is normal. Responsive to the relay *B* is a switch in the field circuit of the generator, which has connected in parallel with it a resistance *E* that, when in circuit, will limit the load on the generator to a point where the motor will pull into synchronism. Therefore, as the voltage on the system builds up after an interruption, before the current in the motor is great enough to operate relay *A*, relay *B* will pick up and trip the field switch, which will cut in the resistance *E* and thereby limit the load on the motor to a point where the motor can pull in without operating relay *A*. It will also be noted that there is a relay *F* which picks up in response to the voltage across resistance *E*, and opens the circuit of the trip coil of the field switch and closes the circuit of the closing coil, so that when the motor pulls into synchronism and the current decreases to normal the field circuit breaker will be closed and the voltage on the generator will be restored to normal; also the voltage across relay *F* will drop to zero and it will reset itself.

The design of synchronous motors affects to a great extent their ability to pull back into synchronism, the greatest item being the resistance of the damper winding. Some motors will not pull back without any load with full voltage applied to the armature, while others with properly designed damper windings will pull back as much as 65 per cent of full load with only 80 per cent of full voltage on the armature. I know of one machine that would not pull in without load that pulled back with full load after its poles had been replaced with ones with very low resistance dampers. However, these low resistance dampers give very low torque at low speed and make it practically impossible to start the motor by applying low voltage at normal frequency to the armature, making it necessary to start with an induction motor. When a heavy current flows in the armature of a synchronous motor while it is out of phase, the fields are subjected to a considerable stress by induction and it is therefore advisable, though not necessary, to insert reactors in the armature leads. This reactance should bring the total of the circuit to about 20 or 25 per cent, and can be provided in the winding of the motor in new machines. This reactance may seem rather high but the motors can be operated at unity power factor under which condition it will have no bad effect, and when the motor gets out of synchronism, the inductance of the armature will be high and its voltage will be in phase with that of the reactance, therefore the voltage across the armature windings will be materially reduced. This is shown graphically in Fig. 7. *A* shows the distribution of voltage between the armature and reactance when the motor is operating at 100 per cent power factor while *B* shows the same when the motor is running out of synchronism.

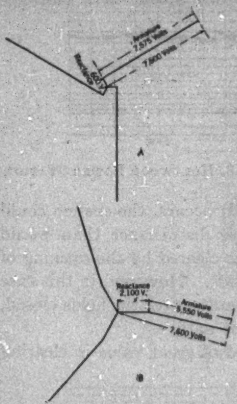

FIG. 7

Fig. 8, which shows a portion of a voltmeter chart taken at a generating station protected by this system during an electrical storm, illustrates the effect of lightning strokes on the service. The voltage was compensated for constant voltage at the supply point, therefore the shape of the curve shows the amount of load dropped and the rate at which it was restored.

The troubles at 4.14 and 4.18 were cleared by the fields being opened after the trouble had been on for four seconds. The trouble at 4.22 was cleared by other devices before the short circuit had been on long enough to cause the fields to open. It will be realized that the instant a severe short circuit occurs the substation machines begin to slow down and, when the fields are set to open after four seconds, will be considerably below speed even before the short circuit is cleared, which adds to the delay in restoring normal conditions.

Fig. 9 shows a section of a voltmeter chart recorded at the same generating station as that shown in Fig. 8. Here the fields of all the generators were opened for one second while there was no trouble on the system, and it will be seen that there was no loss of load. It will be evident that if the fields were set to open instantly when a short circuit occurs, the system could be restored to normal with no more disturbance than would be caused by a short circuit that was cleared by the opening of an oil switch set for one or two seconds. However, in this case the overload relays would have to operate after the fields closed, when the trouble was of a permanent nature.

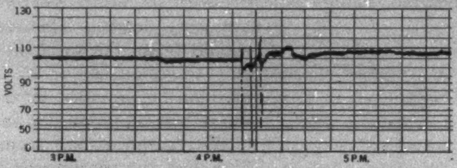

Fig. 8—Voltmeter Chart, June 21, 1913, Holtwood Power Station

In practise, this system has proved of great value in clearing short circuits in the main bus structure, such as are sometimes caused by the failure of an oil switch or the accidental starting of an arc between buses. A further advantage is gained in starting a system after a general shut down, which can be done by closing all the alternating-current switches while the fields are open, and then, when the fields close, all the generators will synchronize and bring the entire system up to normal, no telephoning being necessary, as the voltage will build up gradually and therefore

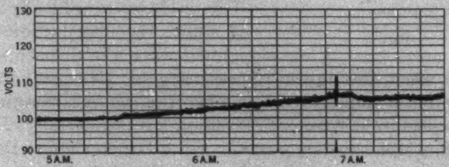

Fig. 9—Voltmeter Chart, Aug. 7,1913, Holtwood Power Station

not damage any machines that may be left in service. This may be done even in cases where the service has been off for 10 or 15 minutes. When there are several generating stations operating in parallel there is no difficulty in getting the field breakers of all generators open at the same time, since the short circuit strikes all the stations simultaneously. If some of the breakers open a little before the others or if some of them do not open at all there is no bad effect.

Up to this point I have discussed only that class of interruptions that affect the entire system. There is, however, another class which affects only a minor part of the system, for example alternating-current distribution feeders that are not tied in with other feeders after they leave the station. More than 50 per cent of the short circuits on these feeders are of a temporary nature, and therefore clear themselves as soon as the feeder trips out; but by the time the operator can close the switch again the motors have shut down. This in effect gives an interruption of several nimutes as the customer will be slow in starting up. Since an arc breaks within a fraction of a second after the voltage is cut off we may, by closing the switch quickly, prevent the motors from shutting down.

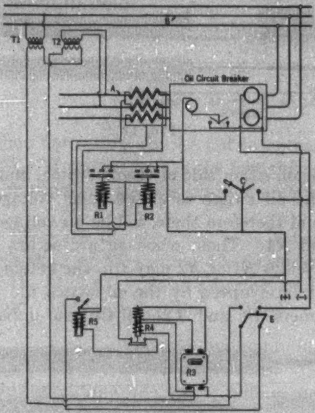

FIG. 10

Fig. 10 illustrates a system that has operated very satisfactorily to clear temporary short circuits on distribution feeders, when the short circuits are of such a nature that they will not reestablish themselves after the arc is once broken.

A feeder *A* is connected through an electrically-controlled oil switch to a station bus *B*. The switch *C* is for operating the switch manually, and relays *R*1 and *R*2 are for tripping the switch in response to current in the feeder, and serve the purpose of the usual overload relays. Transformers *T*1 and *T*2 are connected one on either side of the oil switch, and in such a way that when the oil switch is closed their voltages will oppose each other, and therefore there will be no voltage impressed on relays *R*3 and *R*4. Then, when an arc occurs on the feeder, either of the relays *R*1 or *R*2 may trip the switch but as soon as the current is interrupted by the oil switch the voltage on the two transformers *T*1 and *T*2 will become unbalanced, which will cause current to flow through relays *R*3 and *R*4; *R*4 will pick up instantly, but *R*3 being a time-limit relay will start to move but will not close its contacts for a predetermined time. When relay *R*4 closes its contacts, current will flow through relay *R*5, which will close its contact, and thereby close the oil switch. If the short circuit is still on the feeder when it is made alive, relays *R*1 and *R*2 will trip the switch again and *R*4 and *R*5 will close the switch as soon as the potential across the switch is

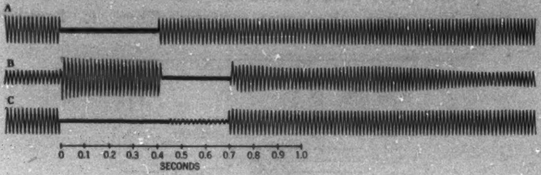

FIG. 11

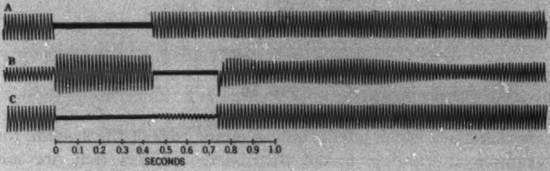

FIG. 12

unbalanced. This opening and closing of the feeder switch will continue until the relay *R*3 closes its contacts, thereby short-circuiting the upper coil of relay *R*4, which will prevent this relay from further operation until the voltage across *R*3 has been reduced to zero for sufficient time for it to return to its starting position. This is done after the trouble on the feeder has been cleared by opening switch *E* and closing the oil switch by means of switch *C*; then the system can be put in operation again by closing switch *E*. If the arc breaks the first time the oil switch opens, *R*3 will return to its starting position making the apparatus self-setting.

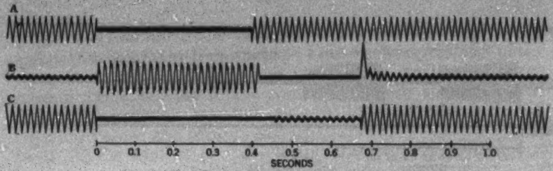

FIG. 13

In order to illustrate the accuracy with which this system operates, and its effect on the service, I have shown oscillograph records, Figs. 11, 12, 13, 14 and 15, which were taken on a 6600-volt system protected by this method. The arc was started by throwing a one-inch (2.54 cm.) spark gap, short-circuited by a fuse wire, across the circuits.

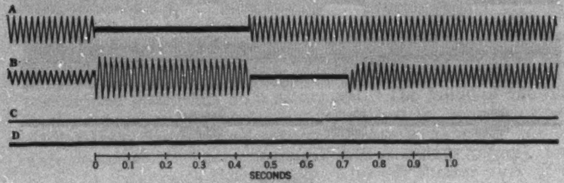

FIG. 14

In Figs. 11 and 12, *A* shows the bus voltage *B* the current in one leg of a 200-h.p. induction motor carrying full load, and *C* the voltage on the feeder. To make the test most severe, the short was made near the switch and the load on the motor was provided by a direct-connected generator supplying current to a resistance, so that the fly-wheel effect would be very small. It will be noted that the time of operation was the same in each case and that the load was not very great after the operation. The conditions under which Fig. 13 was taken were the same as for Figs. 11 and 12, except the motor was running idle. In Fig. 14, *A* gives the voltage on the bus, *B* full-load current in the motor, *C* the voltage of the direct-current generator and *D* the zero line for *C*. It will be noted here that the direct-current voltage remained practically constant showing that the speed of the motor did not drop off materially. Fig. 15 was taken under the same conditions as Figs. 11 and 12 except the spark gap was made so the arc would not break. This shows how the number of operations was limited.

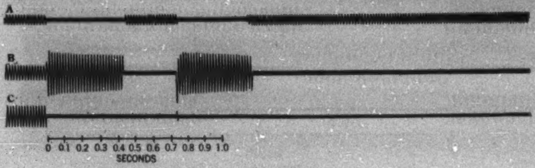

FIG. 15

Fig. 16 shows the operation of the system with a later type oil switch; *A* is the voltage across the switch and therefore shows the time the switch was open, *B* is a timing curve taken from a circuit of 62½ cycles and *C* shows the current in the short circuit. It will be noticed that the switch opened much quicker and closed slower than the old type switch used in the other tests; the total time of operation, however, was about the same.

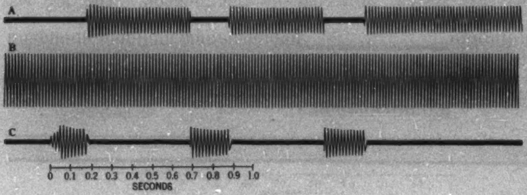

FIG. 16

The tests shown above have been repeated many times and in no case has the time required for similar operations varied more than one fiftieth of a second.

DISCUSSION ON "THE RESTORATION OF SERVICE AFTER A NECESSARY INTERRUPTION" (RICKETTS), CLEVELAND, OHIO, JUNE 27, 1916.

Harold Goodwin, Jr.: These relays presented by Mr. Ricketts in this paper are most interesting, and the results of the operation of the system of the Baltimore Consolidated Gas, Electric Light & Power Company, particularly in connection with the current received from Holtwood show their very great efficiency.

There is one particular point to which I wish to call attention and that is where the text reads: "During the operation of the device, the induction motors will slow down and come back to normal speed, but the relays controlling them should be set for a rather high current, say 400 per cent load, to prevent them from tripping before the motors are up to speed." That is all right, I think, if the motors are all equipped with relays, and if all of the motors were in power plants handled by operatives, but as the system reaches out and reaches down to the smaller users of current, motors are connected without relay equipment but simply fuses. Were all the fuses capable of carrying 400 per cent normal current they would fail in their original purpose of protecting the motor under abnormal conditions and the distribution system under starting conditions. Without going into details let us note that the original purposes of a protective device need serious consideration before an extreme setting is adopted.

R. F. Schuchardt: Fig. 1 shows a balanced relay protection, regarding the efficacy of which I can give testimony. On the system in Chicago we recently had a breakdown in the armature coil of a generator protected with a scheme very similar to that shown by Mr. Ricketts. The generator switch and the field switch were very promptly opened by the relay and the damage in the generator was limited practically to a single coil. The value of the relay in this operation can be better understood by comparing with similar breakdowns which occurred years ago before reactors were installed, the generators having no relays of any kind. In all of these cases the operator, who has a clear view of the generators, saw the flash and very promptly opened the switch but almost invariably all coils were damaged.

The very interesting scheme described, in which the field circuit is opened during certain cases of trouble, is apparently applicable primarily to overhead transmission lines and considerable modification would be necessary to apply it to underground systems. The arrangement shown in Fig. 10 can be applied to distribution circuits almost universally and is of particular value where these circuits are overhead and where disturbances which cause the switch to open are often only momentary. It would be worth while to work out a modification of this scheme applied to an automatic pole-type switch connecting branch circuits, thus reducing the extent of interruptions and thereby still further improving the high record of continuity of service which is now enjoyed by modern systems.

H. R. Woodrow: I agree with Mr. Ricketts regarding the installation of relays on generating circuits. As we have found the burnouts in generators rare, and the reliability of present automatic devices somewhat questionable, we have considered it wise to keep the generator switches non-automatic.

In the generator balanced protective arrangement described in the paper, a loose cable contact, or a slight difference in current transformer characteristics, might cause the relays to operate on straight overload. I would like to inquire if this has ever occurred on any of the systems using this form of protection.

The wonderful improvement in sensibility and reliability of reverse-power relays looks promising for an application in making generator switches automatic.

I would like to ask Mr. Ricketts a question regarding the opening of the generator field circuit. In our experience the opening of a generator field switch has always caused a heavy voltage disturbance on the exciter system. Quite recently a single-phase short circuit occurred in a generator which produced high alternating currents and voltages in the field circuits, causing a severe disturbance on the whole excitation system and control system, which happened to be connected at that time to the exciter bus.

In cases where a considerable generator field resistance or long cable runs are in series with the field circuit, an opening of the field circuit will undoubtedly cause a heavy voltage disturbance in these circuits.

I would also like to inquire if there is any provision made for the speed control when the field circuit is opened? That is, any provision to keep the speed down, as the speed will rise very rapidly if the field circuit is opened and the load is taken off.

Also, when the generators are thrown back in service, what provision is made to prevent arcing at the commutators of the exciters? In one case that I know of, it was attempted to restore service in the manner described, which resulted in serious damage to the exciters by arcing across the commutator. In this case, however, there was no battery floating on the excitation bus.

In general, I do not believe the principle of restoring service as described would be very advantageous to a large concern where there are a large number of underground cable lines, as we very rarely find, in such cases, a disturbance on the system which will clear itself if the voltage is taken off.

We have used to good advantage, on overhead lines, the principle which the author refers to in Fig. 10, but with hand-operated switches. The switches are automatic and they are immediately thrown in once or twice by hand, after they have automatically opened; and in cases of the principal circuits, the operators are instructed to throw the switches in at least twice after they have automatically opened during a lightning storm. In over 50 per cent of the cases the service is restored without further disturbance.

I wish to bring out one point as a warning in accepting this method of restoring service; that is, this method cannot be used unless the switches are completely automatic. That is, unless they will immediately open if thrown in on a short-circuited feeder.

E. T. Street: I notice that the scheme devised for protecting the generators will multiply very largely the number of current transformers on the system. The current transformers on our system have given us a good deal of trouble, and I am of the opinion from what I have read, and I ask if it is correct, that the burning out of one current transformer would shut down the entire station until the transformer was found and isolated. If that is true, I am afraid that the scheme will increase the liability of serious trouble from a small cause.

George A. Burnham: There is one point which might be worthy of consideration, in reference to the elimination of potential on the system to reduce the trouble as a whole, caused by a fault in one of the generators.

It would appear to be a disadvantage to reduce the potential to zero for the length of time which Mr. Ricketts states, in view of the fact that in nearly all of the industrial plants either the individual switches which control the motors or the service switches are equipped with no voltage release of the instantaneous type and the loss of potential at these attachments would undoubtedly disconnect a very large portion of the load on the system.

The arrangements which Mr. Ricketts has described, could, it seems to me, be utilized more effectively and with less liability to interruption of service, if, instead of opening all of the field switches of the generators on the occurrence of the fault in one generator, the balanced relay tripped only the switch of the faulty generator and then allow the movement of the generator switch to disconnect the generator field switch subsequently or simultaneously. This would reduce the potential to zero on the faulty generator instantly after it had been disconnected from the bus and prevent further destruction. It could easily be arranged so that the aforementioned generator field switch would be non-automatic, except when rendered automatic by the operation of the balanced relay, by the addition of an extra contact on the relay which would be connected in series with a circuit-closing switch on the main generator breaker. With this arrangement it would appear to me that the faulty generator could be very satisfactorily disconnected and the potential removed from said generator in order to eliminate further destruction, without it being necessary to remove the potential from the entire system.

John B. Taylor: From the discussion it appears that some members approve certain features of the automatic system, but doubt how far operating and other conditions may be comparable to the systems with which they are more familiar. Devices such as these cannot be applied indiscriminately to any existing system, since much depends on the character of the load; the ratio of cable mileage to overhead lines, the transmission and distribution voltages and the principal causes of interruption.

L. N. Crichton: The part of Mr. Ricketts' scheme that appeals to me most is the service restorer device. Mr. Ricketts has taken quite an active part in the advance of the automatic sectionalizing and it is fitting that he should turn his attention toward methods for restoring service after, for any reason, a circuit has been disconnected.

I recently had the pleasure of seeing that automatic service restorer device in operation, and it was quite remarkable as to the rapidity with which the various pieces of apparatus were put in motion, although there was no induction motor or any load of that kind at the point where I saw the test being made, and I doubt very much whether a man at some little distance away from the motor would have known there had been any momentary interruption of service at all.

It seems to be a scheme particularly useful for high-voltage lines distributing small amounts of power, where the lines extend out in the country for a good many miles, and where lightning conditions are such that if a scheme of that kind is not adopted reliable service could not be given to a good many classes of service. I believe there will be quite an advance in the art of giving continuous service by the use of this device.

Joseph T. Kelly, Jr.: With regard to the point which Mr. Goodwin made, relative to the 400 per cent set of motor relays, I can only say, that the system has been in operation now for something over two years, and we have never heard of a case of trouble of that sort. In fact, as was stated here a moment ago, in most cases—I suppose very close to one hundred per cent of the cases—customers never know that there has been an interruption on the feeder service. Looking at the lights, there is a barely preceptible blink, and looking at a motor it is almost impossible even though watching for it, to notice that there has been any slowing down in the motor at all.

Regarding the application of the scheme to hand-operated switches, so far Mr. Ricketts has not been able to do much work along that line. As a matter of fact, there is one remaining substation of the Consolidated Company equipped with hand-operated switches, and at the present time work is under way to replace all that switchboard equipment with electrically-operated switches equipped with this system, and when that is done all of the substations of the Consolidated Company will be equipped in this manner.

As to the opening of the field circuit causing a disturbance on the exciter system, the point mentioned by Mr. Woodrow, all of our exciters have storage batteries connected with them, and that, doubtless, makes a difference. We do not have any trouble whatever due to the opening of the field switches.

As to the matter of the application of the device to underground cables, of course, when an underground cable breaks down usually the trouble is not of a nature, which clears itself when the potential is cut off. It is usually a permanent breakdown, and consequently though removing the potential and then re-applying it, the trouble would still be present. However, there are cases in which the cable heals itself or will not reestablish an arc when the arc has once been broken. In any event, the momentary application of voltage to the cable cannot do any harm, because the whole cycle takes place in about 7/10 of a second, and there cannot be a sufficient flow of current into the fault in that length of time to cause disastrous results, so that even on an underground system there can be no harm in using this system, and to that extent, I would say, it is not limited to the overhead system. In fact, on the Consolidated system, every feeder going out of a substation, goes out under ground for a greater or less distance, and the automatic opening and closing device is applied to these feeders impartially.

If the trouble is on the overhead, and transient, or if the trouble is on the underground, and clears itself, the system works. Of course, if it is a permanent short circuit the system will not work, and in that case, after the predetermined number of automatic closings the switches will remain open. In our system they are set to close three times, and if they open the fourth time the switch remains open until manually closed.

Mr. Sweet raised the question about the burning out of current transformers. As I understood it, that was in connection with the first scheme for protection of generators. In that case, there are two current transformers, one on each side of the winding of the generator—if either of these burned out, there would, without doubt, be an unbalanced current in the secondaries; in other words, the current in the two current transformers, the one faulty and the other not faulty, would not be maintained, equal, and consequently the relays would operate to cut that generator out of service, including the transformers connected to it, and the system would not be interrupted.

Mr. Burnham raised the point about trouble in a generator causing an interruption on the whole system. That would not be the case because as shown in Fig. 1, in Mr. Ricketts' paper, covering the case of trouble in a generator, if trouble occurs, that generator will be disconnected from the circuit without opening the fields on the rest of the apparatus.

Replying to Mr. Taylor regarding the system; that of the Baltimore Consolidated Gas, Electric Light & Power Company is a 2300/4000-volt four-wire distribution system, the transmission voltage between substations being 13,200 volts with a grounded neutral, and the field-opening device is also used on the 60,000-volt transmission line from the generating station of the Pennsylvania Water & Power Company at Holtwood, Pennsylvania, to Baltimore, although, as Mr, Ricketts mentions incidentally in his paper, in that case the timing device is set for four seconds instead of two seconds, as used in the Consolidated system. The reason for that is that the Pennsylvania Water & Power Company also uses the Nicholson device and Mr. Ricketts' field opening device is so set as to give the Nicholson device a chance to operate first, and then if that fails to clear the trouble, or does not succeed in entirely clearing the trouble, then the field opening device will operate. As Mr. Ricketts points out, that delay of four seconds imposes very much more severe conditions in restoring service.

I have not in mind figures as to the relative amounts of underground and overhead feeders in our system—every feeder, as I said a moment ago, goes out from the substation underground, and the overhead portion is limited to the acutal distribution portion of the feeder; many of the feeders distribute entirely underground, and the system is applied impartially to all feeders. The capacity of our generating station at the present time is approximately 35,000 kv-a. nominally, and will be increased within the next couple of months to about 70,000 kv-a.

I might say, in closing, that the proof of the pudding is in the eating. This system was first applied to a suburban substation at which no operator is kept, something over two years ago, and it has operated with the greatest satisfaction. When a feeder trips out, a relay closes a contact and rings an alarm bell in the office of the district foreman, about three-quarters of a mile distant. That bell may either make two or three, or even one short indication, or it may make three short indications and then continue to ring. In other words, if a feeder drops out and restores at once, and stays in, the alarm bell will so indicate. If it drops out twice and restores itself, the same. If the feeder stays out, the alarm bell continues to operate. So with no operator within three-quarters of a mile this substation is taken care of by this device, and it has been in satisfactory use there for about two years and a half. About one year ago five other substations were equipped with this system, and at the present time the apparatus is ordered with which to equip the last of the substations of the company.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 28, 1916.

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STUDIES IN LIGHTNING PROTECTION ON 4000-VOLT CIRCUITS

BY D. W. ROPER

ABSTRACT OF PAPER

Investigations forming the basis of the paper have been carried on for a period of five years. They were made on a system which at present supplies service to 250,000 customers over some 3000 miles of circuit, through about 16,000 transformers. During the experiments a number of theories have been tried out in practise and the results of the experiments are given in some detail. At the beginning of 1915, three distinct types of arresters and three schemes of protection were in use. The conditions during the year 1915 and the records obtained from lightning storms during the year are set forth by means of a number of maps, drawings and tables. An analysis of the results is followed by a list of conclusions.

The several methods of improving the lightning protection have together resulted in eliminating over 90 per cent of the troubles from lightning.

I—DESCRIPTION OF THE SYSTEM

THE DISTRIBUTING system on which the investigations herein contained were made, covers about 180 square miles in the city of Chicago, and supplies about 250,000 customers through about 16,000 transformers. During the five years covered by these studies, the load has increased from 28,600 kw. to 73,900 kw. The system of distribution is four-wire, three-phase, with 2400 volts (nominally) between each phase wire and the neutral wire, the latter being grounded only at the substations. The system is supplied by 125 feeders from 15 substations, as shown in Fig. 1. All of the feeders leave the substations in four-conductor underground cable, of which there are over 200 miles (321.8 km.) On the average the feeders extend, therefore, nearly two miles (3.2 km.) underground before connecting to the overhead lines, and the length of the overhead feeders is about 25 per cent of the total length. There are, roughly, 3000 miles (4828 km.) of primary distributing mains of which less than 10 per cent is underground. About 100 of the distributing transformers are located in manholes or in transformer vaults on the customers' premises. All of the transformers are connected between the neutral wire and one phase wire, and in the three transformer three-phase installations there is no connection to the neutral wire of the circuit.

There were 15,605 transformers connected to the line on August 1st, 1915, and all of the percentages for that year were based on the records of transformers installed as of that date. A map of the city showing the distribution of transformers is shown in Fig. 2.

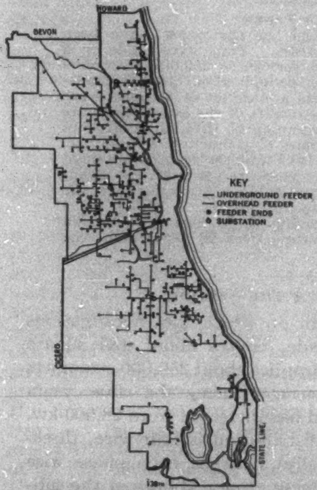

HOWARD
DEVON
KEY
UNDERGROUND FEEDER
OVERHEAD FEEDER
FEEDER ENDS
SUBSTATION
CICERO
STATE LINE
138th

Fig. 1—Map of 4000-Volt Distributing Feeders in Chicago

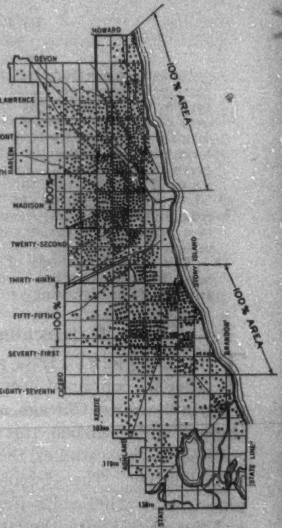

HOWARD
DEVON
LAWRENCE
BELMONT
HARLEM
NORTH
MADISON
TWENTY-SECOND
THIRTY-NINTH
FIFTY-FIFTH
SEVENTY-FIRST
EIGHTY-SEVENTH
CICERO
KEDZIE
103rd
119th
ASHLAND
138th
STATE
STATE LINE
100% AREA
100% AREA
100%
100%
STONY ISLAND
BRANDON

Fig. 2—Transformers in Service in 1915. Each Dot Represents Ten Transformers

II—Preliminary Studies

As the object of the investigation was to improve the service a preliminary study was first made of all of the interruptions on the distribution system, which were classified according to their cause. This showed that transformer troubles were responsible for more interruptions to service than any other single item, and also that a large fraction of all transformer troubles were primarily due to lightning. The need for further investigation of our lightning protection methods was, therefore, very apparent.

Upon requesting the purchasing agent to increase the size of the usual order for lightning arresters, he caused some embarrassment by inquiring what type of arrester had been shown by our experience to be best suited to our purposes. The only answer that could be given to this question was that the arresters had been selected in very much the same manner as our articles of clothing, that is, according to the type which was in fashion at the moment; and further, that the methods of installing the arresters had been such that it was quite impossible to tell from any operating records which arrester, if any, was the best. It was suggested, in the absence of definite information on the subject which would warrant a change in practise, that it seemed advisable to continue to buy arresters of each of the three types that were then in use. As it seemed quite important to determine, if possible, which was the best arrester, it was decided that such changes in the methods of installation should be made as would permit the keeping of records that would assist in securing the desired information.

III—Starting the Investigations

The first step in the investigation was to make a careful record of all transformer fuses blown by lightning during one severe storm. On the following day some of our best troublemen and linemen were sent out to examine carefully these transformers for signs of arcing which could have caused the blowing of the fuse, and in about 80 per cent of the cases the men were successful. Most of the signs indicated arcing on the primary terminal board between the terminals, or from the terminals to the cover. In a smaller number of instances, the arcing had occurred around the primary bushing either inside or outside of the transformers, or between the primary lead and the case. Investigating this matter further it was found that the repair shop had been omitting the terminal boards from all transformers which they rewound, or from those which were turned in with damaged terminal boards. Transformers altered in this manner were found to have a very excellent service record, and it therefore appeared that the advantages of the practise warranted further investigation. For this purpose one circuit was selected in 1911, to which were connected about 250 transformers, and all of the smaller transformers were replaced by others which had their terminal boards removed. The removal of the terminal boards from the larger transformers was accomplished without removing them from the line. This work was completed so late in 1911 that no experience could be obtained during that year from the effects of lightning, and the installation remained without much change during 1912, except that care was taken to see that all additions or alterations to the circuit were made with transformers without terminal boards. No changes in the scheme of lightning protection in use previous to that time were made on this circuit, so that aside from the removal of terminal boards, this circuit was equipped in the same manner as the other circuits.

IV—SEGREGATION OF LIGHTNING ARRESTERS BY CIRCUITS

Previous to the time of starting these investigations, different types of arresters had been ordered in succeeding years, and the additional arresters were installed so as to protect the primary mains which had been extended during the previous year. The general plan was to locate the arresters so that there would be no transformer more than about 1000 ft. (304.8 m.) distant from the nearest arrester. Although this scheme of installation very thoroughly mixed the several types of arresters on the circuits, it was still quite possible to keep records of the failures of arresters so that it could readily be told which one was the greatest hazard to our system; but no information whatever could be secured regarding the relative merits of the several types of arresters as protective devices. In order to secure this information, the plan was therefore adopted of installing only one type of arrester on any one circuit, and a portion of the arresters were moved each year until the segregation of arresters by circuits was completed.

V—LIGHTNING ARRESTERS ON TRANSFORMER POLES

At about the time that these investigations were started, the theory was advanced, that lightning arresters to be most effective should be on the transformer poles. For the purpose of verifying this theory, two circuits were selected early in 1912 on which there were about 300 transformers, and on each circuit an arrester was installed on the same pole with each transformer. A different type of arrester was used on the two circuits. For brevity this plan is hereafter called "100 per cent protection" and the areas are termed 100 per cent areas." This installation differed from our previous practise in that (1) the number of arresters equaled the number of transformers instead of being only a small fraction of their number; (2) the arresters were placed on the transformer poles instead of on the line poles.

VI—ANALYSIS OF RESULTS OBTAINED IN 1912 AND 1913

Late in the year 1912, a study was made of two of the most severe lightning storms which had occurred during the season in an endeavor to find a fair basis for the comparison of the several types of arresters. As the 100 per cent areas showed an almost entire absence of lightning trouble in these two storms, it was at first thought that the solution of the problem had been reached. To check the conclusion, a map of the city was prepared on which the 100 per cent areas were shown by colored pasters. Then the areas covered by other circuits on which there had been no trouble whatever during the same storms was shown by pasters of a different color. Upon completion of the map it was discovered that there were a number of areas, protected only by a few arresters on the line poles, which were entirely free from lightning trouble, some of them being located adjacent to the 100 per cent areas.

The records of this year, and the map with the pasters of several colors showing the circuits on which there was no trouble, indicated very plainly that it was quite impossible to definitely determine from the records, or from any subsequent examination on the ground, whether the freedom from trouble was due to the perfection of the protection or to absence of lightning, and no method has yet been discovered for overcoming the difficulty. The cause of the difficulty is the fact that, the only means available for determining the presence of lightning and its relative intensity, is by the phenomona that are to be reduced by means of the improved lightning protection; and that having installed the lightning arresters and discovered a reduction in the trouble, there is no means of telling how much trouble there would have been were the lightning arresters absent. For the same reason it is impossible to recognize a uniformly distributed lightning storm, should it occur, although such a storm would greatly simplify these investigations. An endeavor was made to secure an independent reference standard by consulting the records of the telephone company, but it was found that during the period covered by these investigations, they were rapidly replacing their overhead open wire construction with aerial cable, and that this change greatly reduced the amount of trouble on their lines during lightning storms.

As a result of the experience in 1912, it was decided that the scheme of installing the arresters on the transformer poles gave promise of beneficial results, and that in order to secure more reliable information regarding the relative merits of the several types of arresters, the 100 per cent areas should be enlarged by the addition of several circuits, each having but one type of arrester.

The information obtained from the circuit from which the terminal boards had been removed, was indefinite and not at all conclusive, due apparently, to the fact that a sufficient number of transformers were not included in the experiment. It was, therefore, decided to remove the terminal boards from a larger number of transformers, so that at the opening of the lightning season in 1913, there were a total of about 1600 transformers which had been altered in this manner.

The records obtained during 1913 demonstrated, first, that the removal of the terminal boards from transformers would eliminate about 60 per cent of the troubles due to lightning, and second, that the installation of lightning arresters on the same pole with each transformer made a very considerable further reduction in the amount of trouble from lightning, as compared with our previous practise of installing a few arresters on the line poles. (The experiments from which these results were obtained were described in further detail in a paper read by the author before the Pittsfield meeting of the A. I. E. E., May, 1914.)

As a result of the experiments with the terminal boards, it was decided that it was desirable to remove the terminal boards from all transformers which were returned to the storeroom for any reason, and orders to this effect were issued early in 1914. At about the same time it was specified that all new transformers should be without terminal boards. During the period that has elapsed since these changes in our practise were adopted, the number of transformers from which the terminal boards were removed has approximately equaled the new transformers installed on our lines, each figure being about 10 per cent per year.

VII—Ratio between Fuses Blown and Transformers Burned Out

In the investigation of the storms that occurred in 1912, it was noted that a fairly constant ratio existed between the number of blown primary fuses and the transformers burned out by lightning. As the number of burnouts by lightning per year was approximately 125, and as the number of transformers in the 100 per cent areas was only a small fraction of the total, it was thought that more accurate data and a better comparison of the several types of arresters could be secured by using the larger number. It was, therefore, arranged to keep careful records of all primary fuses blown, as well as of the transformer burnouts. These records and the ratio of the two quantities over a period of four years is shown in Fig. 3. From this figure it is very apparent that, while the ratio may perhaps be fairly constant during one lightning season, it has decreased very considerably during the four years. It is therefore quite impossible to use the record of blown primary fuses instead of the record of burned out transformers, in the manner described, for the purpose of comparing one year's records with another. The meaning of the reduction in the ratio will be discussed in connection with the results obtained during 1915.

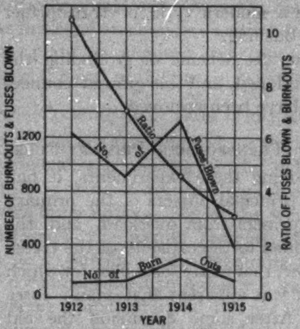


FIG. 3—RECORD FOR SEVERAL YEARS OF PRIMARY FUSES BLOWN AND TRANSFORMERS BURNED OUT BY LIGHTNING AND THEIR RATIO

VIII—GROUNDING OF TRANSFORMER CASES

The theory was also advanced that the grounding of the transformer cases would improve the lightning protection. In order to test this theory, three circuits on which there were about 600 transformers were selected, and each of the transformer cases was connected to the lightning arrester ground wire through a primary cut-out. This cut-out, with a piece of copper wire in place of the fuse, was located so that a lineman climbing the pole could readily remove the plug from the cut-out, and in this manner remove any hazard which might exist due to the grounded transformer case. Careful records were kept of this installation for a number of years. While it is entirely possible that the number of transformers included in the experiment was inadequate for the purpose, and the records misleading due to the variableness of lightning storms, the results for three years appear to indicate that the grounding of the transformer cases has but little effect upon the efficiency of the lightning protection. As a matter of fact, there was slightly more trouble on these particular circuits than the average for other circuits, this trouble taking the nature of the burning off of the primary leads at or near the primary bushings. The area which was selected for this trial happened to be one of the older districts containing transformers which were considerably above the average age of all on the system. It is possible that the results would have been different with a modern type of transformer supplied with a larger primary bushing.

For the reasons above given, the scheme of grounding the transformer cases has been abandoned, and the ground connections installed for this purpose have been removed.

IX—Increasing the Size of Transformer Primary Fuses

Previous to the time of starting these experiments, it had been assumed that one of the principal objects of the primary fuse was to protect the transformers from overload, and the sizes of the fuses were proportioned to the capacity of the transformer. It was noted, however, that many fuses blew for which no cause could be found, and it was apparent that many fuses were blowing unnecessarily. After some discussion the old theory was abandoned, and instead a new theory was adopted, that the object of the primary fuse was to protect the service by disconnecting a defective transformer. As there were only two types of cut-outs in use, 25-ampere fuses were determined upon for use in the smaller cut-out for all transformers up to and including 10 kw., and 40-ampere fuses in the larger cut-out for transformers from 15 to 40-kw. capacity. Larger transformers are generally connected to the line without cut-outs. This rule, adopted in March 1914, was made to apply to all transformers installed, or to any fuses replaced for any reason after that date. This change in practise has resulted in a large reduction in the number of transformer fuses blown by other causes than lightning, but it is not clear that this change would have any serious effect on the blowing of fuses due to lightning, as this would mean that an arc started by the lightning would blow a five ampere fuse, for example, but that the arc might go out automatically without blowing a 25-ampere fuse. The facts in the case are set forth, however, as it is possible that other engineers will not be entirely in accord with the author on this point.

X—Changes Made in 1914

As a result of the experiments with arresters on transformer poles, plans were adopted early in 1914, calling for some considerable additions to the 100 per cent areas for each of the several types of arresters. On account of the conditions existing at that time and the pressure of new construction work, the lightning arrester changes and additional installations were only partially completed before the opening of the lightning season. As further disturbances occurred during the middle of the summer the plans as adopted were not completely carried out until after the end of the year.

XI—Conclusions from the Records Obtained in 1914

As the changes planned for the year were only partially completed at the opening of the lightning season, and were not entirely completed until after the end of the year, the conditions were quite unfavorable for the securing of any accurate records. Although the results obtained during this year added very little to our knowledge regarding the best type of arresters, the records continued to indicate a very decided advantage for the scheme which is termed 100 per cent protection; and it further appeared that comparatively little benefit was being received from the lightning arresters installed on the line poles. As a result of this information, it was decided early in 1915 to increase the 100 per cent protection areas, (1) by moving all arresters on line poles, about 1000 in number, to the transformer poles, and (2) by installing about 3000 additional arresters. The 100 per cent areas completed previous to this time formed a broad ban across the city on the south side, in addition to a few small isolated areas on the north side. In planning the work for 1915, it was, therefore, arranged to extend the 100 per cent areas on the north side in such a manner that they would form a second band across this side of the city, and located so that it would include the most important customers. The increase year by year in the 100 per cent areas is shown in Fig. 4.

XII—Segregation of Lightning Arresters by Definite Boundaries

During the several years in which the scheme of segregating arresters by circuits had been followed, the number of primary circuits had been increasing about 25 per cent per year. As new circuits were installed to handle the increase in load, it was necessary to move a considerable number of arresters each year in order to have only one type of arrester on each circuit. The plan was, therefore, changed so as to use streets, generally section lines, for the boundaries of the various lightning arrester districts. This change not only eliminated the annual expense of moving arresters, which was continually increasing, but it also greatly simplified the keeping of the records and their subsequent analysis.

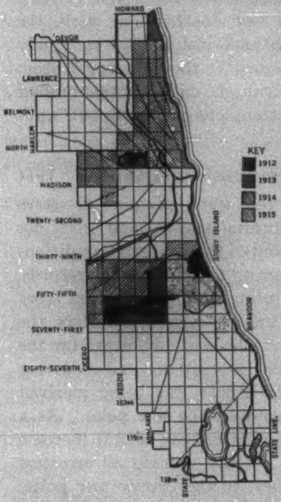

HOWARD
DEVON
LAWRENCE
BELMONT
HARLEM
NORTH
MADISON
TWENTY-SECOND
THIRTY-NINTH
FIFTY-FIFTH
SEVENTY-FIRST
CICERO
EIGHTY-SEVENTH
KEDZIE
103RD
ASHLAND
119TH
138TH
STATE
STATE LINE
STONY ISLAND
BRANDON
KEY
1912
1913
1914
1915

FIG. 4—MAP SHOWING 100 PER CENT AREAS FOR EACH YEAR 1912-1915

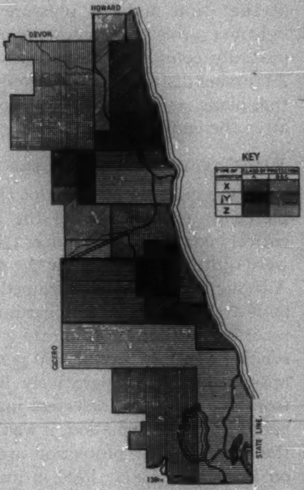

HOWARD
DEVON
CICERO
STATE LINE
138TH
KEY
X
Y
Z
A

FIG. 5—MAP SHOWING SUB-DIVISION OF CITY BY TYPE OF ARRESTER AND CLASS OF PROTECTION DURING 1915

III—INSTALLATION OF ARRESTERS ON TRANSFORMER POLES OUTSIDE THE 100 PER CENT AREAS

As the results of the experience obtained in 1912 indicated that a considerable improvement in the service could be secured by the installation of arresters on the transformer poles, it was decided that the extra expense of such installations was warranted in the case of important customers. Beginning in February, 1913, the plan was therefore adopted, of installing a lightning arrester on the same pole with each transformer of 15-kw. capacity or larger. In March, 1914, this rule was altered so as to include all transformers of 7.5 kw. and larger, which were thereafter installed, changed or moved. A few weeks later the rule was extended so as to include all transformers for supplying power customers, regardless of their size. In April, 1915, the rule was again altered so as to include all transformers above 3-kw. capacity.

XIV—CONDITIONS AT THE BEGINNING OF 1915

At the opening of the lightning season in 1915 there were in service three classes of protection, designated hereinafter as classes A, B and C and described as follows:

Class A. This includes the transformers which have an arrester on the same pole, and which are located in the so-called 100 per cent areas, that is, in areas in which each transformer is similiarly protected.

Class B. This includes the transformers outside of the 100 per cent areas, which are protected by arresters on the same pole, as the result of the rules adopted from time to time and set forth under heading XIII.

Class C. This includes all transformers that are not protected by arresters on the same pole, and together with the class B includes all transformers outside the 100 per cent areas.

All transformers included in this investigation come under one of the three above described classes. There are no lightning arresters installed on line poles for the protection of transformers, except in a very few isolated cases where the equipment of other companies on jointly owned transformer poles interfered with the installation of the arrester on such poles.

The manner in which the several types of arresters were distributed throughout the city is shown in Fig. 5. The letters *X*, *Y* and *Z* used on this map serve to designate the several types of arresters, and these letters are used throughout the various tables and discussions. The heavy shading on this map indicates the 100 per cent protection areas, and for convenience in making comparisons, the boundaries of these areas have been shown by heavy lines on other similar maps. Each of the several areas

TABLE I.
DATA ON THE SIZES OF THE TRANSFORMERS IN THE SEVERAL DISTRICTS

Area No.	Type of arrester	Class of protection	Sq. mile	No. of transformers				Transformer per sq. mile
				Below 5 kv-a.	5 to 15 kv-a.	Above 15 kv-a.	Total	
3	X	A	7.8	327	779	193	1299	167
8	..	..	3.0	126	138	16	280	93
16	..	..	4.0	228	344	138	710	178
..	..	..	14.8	681	1261	347	2289	155
5	Y	A	6.5	392	759	160	1311	202
7	..	..	3.0	160	280	52	492	164
13	..	..	7.0	313	489	173	975	139
			16.5	865	1528	385	2778	168
6	Z	A.	4.3	132	378	80	590	137
14	..	..	9.0	281	178	47	506	56
15	..	..	3.0	100	185	129	414	138
18	..	..	2.0	127	64	3	194	97
1	..	..	0.8	38	73	6	117	130
17	..	..	7.5	420	259	35	714	95
..	..	..	26.6	1098	1137	300	2535	95
TOTAL	ALL	A	57.9	2644	3926	1032	7602	131
2	X	B	7.0	13	29	18	60	9
10	..	..	7.5	13	97	88	198	26
..	..	..	14.5	26	126	106	258	18
4	Y	B	28.5	28	67	41	136	5
11	..	..	9.2	69	180	109	358	39
20	..	..	19.5	35	54	37	126	7
21	..	..	2.0	1	3	1	5	3
..	..	..	59.2	133	304	188	625	11
9	Z	B	9.2	51	209	145	405	45
12	..	..	3.0	11	6	14	31	10
19	..	..	36.5	139	186	61	386	11
..	..	..	48.7	201	401	220	822	17
TOTAL	ALL	B	122.4	360	831	514	1705	14
2	X	C	7.0	221	129	44	394	56
10	..	..	7.5	378	392	54	824	110
..	..	..	14.5	599	521	98	1218	84
4	Y	C	28.5	926	542	36	1504	53
11	..	..	9.2	355	362	49	746	81
20	..	..	19.5	429	146	11	586	30
21	..	..	2.0	35	7	6	48	24
..	..	..	59.2	1725	1057	102	2884	49
9	Z	C	9.2	340	643	93	1076	117
12	..	..	3.0	37	23	6	66	33
19	..	..	36.5	742	300	12	1054	29
..	..	..	48.7	1119	966	111	2196	45
TOTAL	ALL	C	122.4	3443	2544	311	6298	51
GRAND TOTALS		ALL	180.3	6447	7301	1857	15,605	85

was given a number and these numbers are used consistently throughout the records, but in order to avoid confusion, have been omitted from the map.

In order to assist in analyzing the results, the transformers were divided into three classes according to their size, and the number of each of the three classes in each of the areas is given in Table I. For the simplification of the calculations, the number of transformers in service on August 1st, 1915, which was approximately the middle of the lightning season, was taken as the basis of this table. From this information the percentage distribution of the transformers in the territories corresponding to each type of arrester and class of protection is shown in Table II.

TABLE II.

SUMMARY OF LIGHTNING ARRESTER DISTRICTS, SHOWING THE PERCENTAGE DISTRIBUTION OF THE TRANSFORMERS AMONG THE DISTRICTS BY GROUPS OF SIZES.

Class of protection	Type of arrester	Distribution per cent.			
		Below 5 kv-a.	5 to 15 kv-a.	Above 15 kv-a.	Total
A	X	30	15	55	100
..	Y	31	55	14	100
..	Z	43	45	12	100
..	ALL	35	51	14	100
B	X	10	49	41	100
..	Y	21	49	30	100
..	Z	24	49	27	100
..	ALL	21	49	30	100
C	X	49	43	8	100
..	Y	60	37	3	100
..	Z	51	44	5	100
..	ALL	55	40	5	100
A B C	X	35	50	15	100
..	Y	43	46	11	100
..	Z	43	45	12	100
..	ALL	41	47	12	100

XV—RECORDS OBTAINED IN 1915

A list of all the transformers burned out by lightning during the year with the size, area number, type of arrester and class of protection for each transformer is given in Table III.

TABLE III.
CLASSIFIED LIST OF TRANSFORMERS BURNED OUT BY LIGHTNING IN 1915.

Type of arrester				X			Y			Z			Nature of burnout
Class of protection				A	B	C	A	B	C	A	B	C	
No. of storm	Date	Size of transformer kw.	Area No.										
1	May 3	10	9	..	..	..	..	..	..	..	..	×	Damaged
2	15	7½	2	..	×	..	..	..	..	..	..	..	Coils
		1½	2	..	..	×	..	..	..	..	..	..	•
		7½	4	..	..	×	..	..	..	..	..	..	•
		1½	4	..	..	×	..	..	..	..	..	..	•
		1	6	..	..	..	..	..	..	×	..	..	Damaged
		3	6	..	..	..	..	..	..	×	..	..	•
		7½	9	..	..	..	..	..	..	..	..	×	•
		2	9	..	..	..	..	..	..	..	..	×	•
		4	10	..	..	×	..	..	..	..	..	..	Coils
		3	10	..	..	×	..	..	..	..	..	..	•
		2	10	..	..	×	..	..	..	..	..	..	Damaged
		10	11	..	..	..	..	..	×	..	..	..	•
		1½	12	..	..	..	..	..	..	..	..	×	•
		3	14	..	..	..	..	..	..	×	..	..	Coils
		3	14	..	..	..	..	..	..	×	..	..	Damaged
		5	14	..	..	..	..	..	..	×	..	..	Coils
		15	15	..	..	..	..	..	..	×	..	..	•
		3	17	..	..	..	..	..	..	×	..	..	•
		5	17	..	..	..	..	..	..	×	..	..	Damaged
		5	17	..	..	..	..	..	..	×	..	..	Coils
		4	19	..	..	..	..	..	..	..	×	..	•
		5	20	..	..	..	..	..	×	..	..	..	Damaged
		10	20	..	..	..	..	..	×	..	..	..	•
		1½	20	..	..	..	..	..	×	..	..	..	Coils
3	June 7	10	9	..	..	..	..	..	..	..	..	×	•
		7½	6	..	..	..	..	..	..	×	..	..	Damaged
4	11	5	11	..	..	..	..	..	×	..	..	..	•
		5	9	..	..	..	..	..	..	..	×	..	Coils
5	12	4	4	..	..	..	..	..	×	..	..	..	Damaged
		1½	4	..	..	..	..	..	×	..	..	..	•
		1½	4	..	..	..	..	..	×	..	..	..	•
		1½	4	..	..	..	..	..	×	..	..	..	•
		4	4	..	..	..	..	..	×	..	..	..	Coils
		3	4	..	..	..	..	..	×	..	..	..	•
		1½	4	..	..	..	..	..	×	..	..	..	Damaged
		7½	4	..	..	..	..	..	×	..	..	..	•
		50	11	..	..	..	..	..	×	..	..	..	•
		2	11	..	..	..	..	..	×	..	..	..	•
		3	18	..	..	..	..	..	..	×	..	..	Coils
		2	19	..	..	..	..	..	..	..	..	×	•
		1½	19	..	..	..	..	..	..	..	..	×	•
		5	20	..	..	..	..	..	×	..	..	..	•
6	July 10	1½	19	..	..	..	..	..	..	..	..	×	Damaged
		5	19	..	..	..	..	..	..	..	..	×	•
Carried Forward				0	1	6	0	0	16	11	2	9	45

TABLE III. (*Continued*)
CLASSIFIED LIST OF TRANSFORMERS BURNED OUT
BY LIGHTNING IN 1915.

Type of arrester				X			Y			Z			Nature of burnout
Class of protection				A	B	C	A	B	C	A	B	C	
No. of storm	Date	Size of transformer kw.	Area No.										
Brought Forward				0	1	6	0	0	16	11	2	9	45
7	July 11	1½	19	..	..	..	..	..	..	..	..	×	Coils
		2	11	..	..	..	..	..	×	..	..	..	"
8	12	3	17	..	..	..	..	..	..	×	..	..	"
9	14	7½	13	..	..	..	×	..	..	..	..	..	Damaged
		1½	19	..	..	..	..	..	..	..	..	×	Coils
		10	16	×	..	..	..	..	..	..	..	..	Damaged
10	15	5	19	..	..	..	..	..	..	..	..	×	Coils
11	18	3	10	..	..	×	..	..	..	..	..	..	"
		7½	9	..	..	..	..	..	..	..	..	×	"
		15	9	..	..	..	..	..	..	..	×	..	"
12	Aug. 14	20	3	×	..	..	..	..	..	..	..	..	Damaged
		1½	5	..	..	..	×	..	..	..	..	..	Coils
		4	4	..	..	..	..	..	×	..	..	..	"
		7½	4	..	..	..	..	..	×	..	..	..	Damaged
		2	4	..	..	..	..	..	×	..	..	..	"
		1½	4	..	..	..	..	..	×	..	..	..	"
		1½	4	..	..	..	..	..	×	..	..	..	Coils
		1	20	..	..	..	..	..	×	..	..	..	"
		2	20	..	..	..	..	..	×	..	..	..	"
13	Aug. 16	2	17	..	..	..	..	..	..	×	..	..	"
		3	19	..	..	..	..	..	..	..	..	×	"
		7½	19	..	..	..	..	..	..	..	..	×	Damaged
		4	19	..	..	..	..	..	..	..	..	×	"
		3	19	..	..	..	..	..	..	..	..	×	"
		1½	19	..	..	..	..	..	..	..	..	×	Coils
		1	19	..	..	..	..	..	..	..	..	×	Damaged
		5	19	..	..	..	..	..	..	..	..	×	"
		3	19	..	..	..	..	..	..	..	..	×	Coils
		2	19	..	..	..	..	..	..	..	..	×	Damaged
		1	19	..	..	..	..	..	..	..	..	×	Coils
		10	19	..	..	..	..	..	..	..	..	×	Damaged
		5	20	..	..	..	..	..	×	..	..	..	Coils
		2	20	..	..	..	..	..	×	..	..	..	"
		2	20	..	..	..	..	..	×	..	..	..	Damaged
		1	20	..	..	..	..	..	×	..	..	..	"
		7½	20	..	..	..	..	..	×	..	..	..	Coils
		5	20	..	..	..	..	..	×	..	..	..	"
		1½	20	..	..	..	..	..	×	..	..	..	Damaged
		2	20	..	..	..	..	..	×	..	..	..	Coils
		2	20	..	..	..	..	..	×	..	..	..	Damaged
		2	20	..	..	..	..	..	×	..	..	..	Coils
		4	20	..	..	..	..	..	×	..	..	..	"
		1½	20	..	..	..	..	..	×	..	..	..	Damaged
		2	20	..	..	..	..	..	×	..	..	..	Coils
		3	20	..	..	..	..	..	×	..	..	..	"
Carried Forward				2	1	7	2	0	38	13	3	24	90

Vol. 35
1916

TABLE III. (*Continued*)
CLASSIFIED LIST OF TRANSFORMERS BURNED OUT BY LIGHTNING IN 1915.

Type of arrester				X			Y			Z			Nature of burnout
Class of protection				A	B	C	A	B	C	A	B	C	
No. of storm	Date	Size of transformer kw.	Area No.										
Brought Forward				2	1	7	2	0	38	13	3	24	90
13	Aug. 16	1	20	..	..	..	..	..	×	..	..	..	Coils
		3	20	..	..	..	..	..	×	..	..	..	•
		7½	20	..	..	..	..	..	×	..	..	..	Damaged
		1½	20	..	..	..	..	..	×	..	..	..	•
		3	20	..	..	..	..	..	×	..	..	..	Coils
		2	20	..	..	..	..	..	×	..	..	..	•
		1½	20	..	..	..	..	..	×	..	..	..	•
		3	20	..	..	..	..	..	×	..	..	..	•
		3	20	..	..	..	..	..	×	..	..	..	•
		3	20	..	..	..	..	..	×	..	..	..	•
		4	20	..	..	..	..	..	×	..	..	..	Damaged
		7½	21	..	..	..	..	..	×	..	..	..	Coils
		2	21	..	..	..	..	..	×	..	..	..	•
14	Aug. 23	3	13	..	..	..	..	..	×	..	..	..	•
		7½	11	..	..	..	..	..	×	..	..	..	•
15	Sep. 8	1½	4	..	..	..	..	..	×	..	..	..	Damaged
		3	4	..	..	..	..	..	×	..	..	..	Coils
		2	4	..	..	..	..	..	×	..	..	..	•
		3	4	..	..	..	..	..	×	..	..	..	Damaged
		3	4	..	..	..	..	..	×	..	..	..	Coils
		1½	4	..	..	..	..	..	×	..	..	..	•
		7½	5	..	..	..	×	..	..	..	..	..	•
		2	9	..	..	..	..	..	..	..	..	×	•
		1½	10	..	..	×	..	..	..	..	..	..	•
		5	14	..	..	..	..	..	..	..	..	×	Damaged
		3	19	..	..	..	..	..	..	..	×	..	Coils
		2	19	..	..	..	..	..	..	..	..	×	•
		3	19	..	..	..	..	..	..	..	..	×	•
		2	19	..	..	..	..	..	..	..	..	×	•
16	Sep. 10	20	7	..	..	..	..	..	×	..	..	..	Damaged
		3	18	..	..	..	..	..	..	×	..	..	Coils
		5	18	..	..	..	..	..	..	×	..	..	•
		1	19	..	..	..	..	..	..	..	..	×	Damaged
GRAND TOTAL				2	1	8	3	0	60	15	4	30	73 Coils 50 Damage

"Damaged" means transformer disabled by damage to leads or otherwise without injuring coils.

The location of all the transformers burned out by lightning in 1915 is shown in Fig. 6, and the fuses blown by lightning are shown in a similar way in Fig. 7. By comparing these maps with Fig. 2 it will be noted that in the 100 per cent areas where the transformers are most numerous, the burnouts and fuses blown were quite scattering, while outside of the 100 per cent areas, in which regions the transformers are not so numerous that the burn-outs and fuses blown are more numerous, thus indicating a distinct reduction in the percentage of burn-outs and fuses blown within the 100 per cent areas.

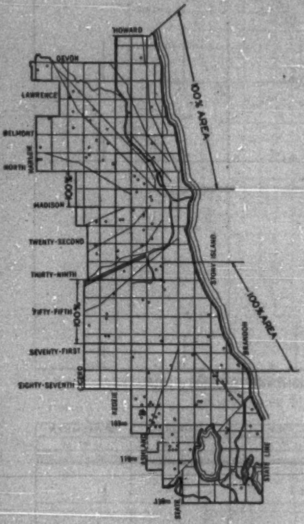

HOWARD
DEVON
LAWRENCE
BELMONT
NORTH
HARLEM
100%
MADISON
TWENTY-SECOND
THIRTY-NINTH
FIFTY-FIFTH
100%
SEVENTY-FIRST
EIGHTY-SEVENTH
CICERO
KEDZIE
103rd
ASHLAND
119th
138th
STATE
STATE LINE
STONY ISLAND
BRANDON
100% AREA
100% AREA

FIG. 6—TRANSFORMER BURN-OUTS DUE TO LIGHTNING 1915. EACH DOT REPRESENTS ONE BURN-OUT

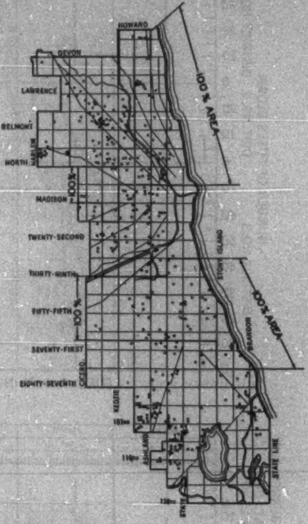
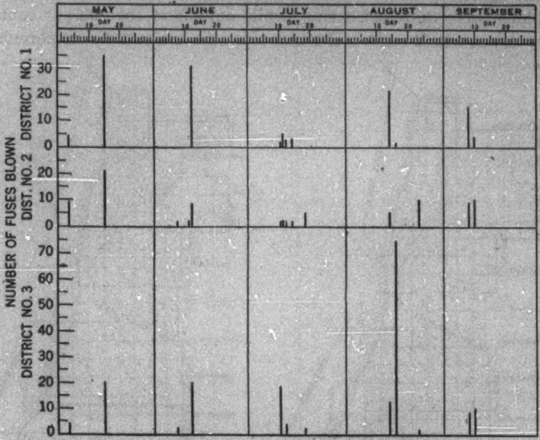

HOWARD
DEVON
LAWRENCE
BELMONT
NORTH
HARLEM
100%
MADISON
TWENTY-SECOND
THIRTY-NINTH
FIFTY-FIFTH
100%
SEVENTY-FIRST
EIGHTY-SEVENTH
CICERO
KEDZIE
103rd
ASHLAND
119th
138th
STATE
STATE LINE
STONY ISLAND
BRANDON
100% AREA
100% AREA

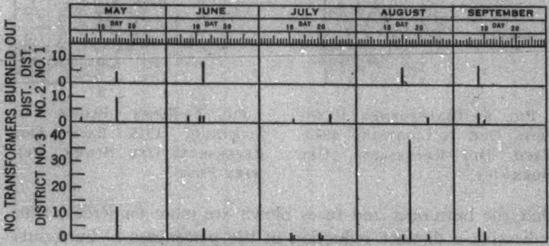
FIG. 7—FUSES BLOWN BY LIGHTNING 1915. EACH DOT REPRESENTS ONE BLOWN PRIMARY FUSE

Fig. 8 is a diagram showing the number of fuses blown and transformers burned out by lightning during the year, the arrangement being by districts. The boundaries of the districts are North Avenue and 39th Street, extending across the city from east to west. The districts are numbered in order, District

No. 1 being at the north and No. 3 at the south end of the city. This diagram shows how the various lightning storms were distributed throughout the season and among the various sections of the city. From this diagram the impression is obtained that



FUSES BLOWN IN LIGHTNING STORMS - 1915.



TRANSFORMERS BURNED OUT BY LIGHTNING - 1915.

FIG. 8

the storms of May 15th and August 16th were somewhat more erratic than the other storms and for the purpose of elucidating this point, the effects of these two storms are shown graphically in Figs. 9 and 10.

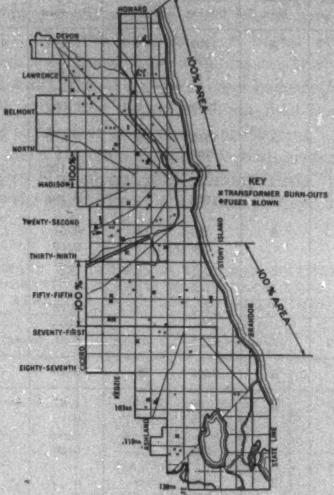

HOWARD
DEVON
LAWRENCE
BELMONT
NORTH
MADISON
TWENTY-SECOND
THIRTY-NINTH
FIFTY-FIFTH
SEVENTY-FIRST
EIGHTY-SEVENTH
CICERO
KEDZIE
103rd
ASHLAND
119th
138th
STATE
100% AREA
100%
100%
KEY
× TRANSFORMER BURN-OUTS
● FUSES BLOWN
STONY ISLAND
100% AREA
BRANDON
STATE LINE

FIG. 9—TRANSFORMER BURN-OUTS AND FUSES BLOWN BY LIGHTNING STORM MAY 15, 1915

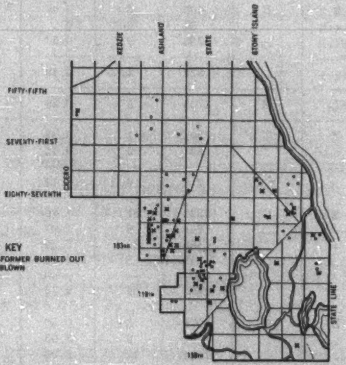

KEDZIE
ASHLAND
STATE
STONY ISLAND
FIFTY-FIFTH
SEVENTY-FIRST
CICERO
EIGHTY-SEVENTH
103rd
119th
138th
KEY
× TRANSFORMER BURNED OUT
● FUSE BLOWN
STATE LINE

FIG. 10—LIGHTNING STORM OF AUG. 16, 1915

TABLE IV

RECORD OF TROUBLES DUE TO LIGHTNING STORMS DURING 1915. ARRANGED BY AREAS.

Area No.	Type of arrester	Class of protection	Transformers in area	Transformers burned out		Primary fuses blown only	
				No.	Per cent	No.	Per cent
3	X	A	1299	1	0.077	17	1.31
8	..	..	280	0	0	3	1.07
16	..	..	710	1	0.141	6	0.84
..	..	..	2289	2	0.087	26	1.13
5	Y	A	1311	2	0.015	19	1.45
7	..	..	492	0	0.	5	1.02
13	..	..	975	1	0.102	11	1.13
..	..	..	2778	3	0.108	35	1.26
6	Z	A	590	3	0.51	8	1.35
14	..	..	506	3	0.59	7	1.38
15	..	..	414	1	0.24	7	1.69
18	..	..	194	3	1.54	5	2.58
1	..	..	117	0	0	0	0
17	..	..	714	5	0.70	9	1.26
..	..	..	2535	15	0.59	36	1.42
TOTAL	ALL	A	7602	20	0.26	97	1.27
2	X	B	60	1	1.67	0	0
10	..	..	198	0	0	2	1.01
..	..	..	258	1	0.39	2	0.77
4	Y	B	136	0	0	1	0.73
11	..	..	358	0	0	2	0.56
20	..	..	126	0	0	0	0
21	..	..	5	0	0	0	0
..	..	..	625	0	0	3	0.48
9	Z	B	405	2	0.49	4	0.98
12	..	..	31	0	0	0	0
19	..	..	386	2	0.52	5	1.29
..	..	..	822	4	0.49	9	1.09
TOTAL	ALL	B	1705	5	0.29	14	0.82
2	X	C	394	1	0.25	16	4.06
10	..	..	824	5	0.61	19	2.31
..	..	..	1218	6	0.49	35	2.88
4	Y	C	1504	21	1.40	72	4.78
11	..	..	746	8	1.07	16	2.14
20	..	.	586	31	5.29	88	15.01
21	..	..	48	2	4.16	0	0
..	..	..	2884	62	2.14	176	6.10
9	Z	C	1076	6	0.56	25	2.32
12	..	..	66	2	3.03	0	0
19	..	..	1054	22	2.08	35	3.32
			2196	30	1.36	60	2.73
TOTAL	ALL	C	6298	98	1.56	271	4.30
GRAND TOTALS			15,605	123	.79	382	2.44

Table IV gives a record, by areas, of the transformer trouble due to lightning, segregated by the type of arrester and class of protection. For the purpose of a better comparison the percentage figure of transformer troubles for the various classes of protection and types of arresters have been collected in Table V. Table Vᴀ shows the nature of damage to the transformers for each type of arrester and class of protection.

Tables VI and VII give a classified record, arranged by storms, of transformers burned out and primary fuses blown respectively during the year. From these tables, Figs. 11 and 12 have been prepared, showing graphically the variations during the season of the percentage of transformers burned out and fuses blown. These tables and the figures also show plainly the erratic nature of the storms of May 15th and August 16th. It will be noted, for example, that 60 per cent of the total number of burn-outs for type *Z* arrester and class A protection occurred on May 15th, although the total number of transformers burned out on this day was only 20 per cent of the total occurring dur-the season.

TABLE V.

SUMMARY OF LIGHTNING TROUBLES DURING 1915, SHOWING THE RESULTS FOR EACH TYPE OF ARRESTER AND CLASS OF PROTECTION.

Class of protection	Type of arrester	Burn-outs per cent	Fuses blown per cent
A	X	0.087	1.13
..	Y	0.108	1.26
..	Z	0.50	1.42
	ALL	0.26	1.27
B	X	0.39	0.77
..	Y	0	0.48
..	Z	0.49	1.09
..	ALL	0.29	0.82
C	X	0.49	2.85
..	Y	2.14	6.10
..	Z	1.36	2.73
	ALL	1.56	4 30

Table VIII gives data regarding the transformer troubles for each size of transformer. These troubles have been further

TABLE NO. 5-A

TRANSFORMERS BURNED OUT BY LIGHTNING DURING 1915 CLASSIFIED BY TYPE OF PROTECTION AND EXTENT OF DAMAGE.

	No. of burn-outs							
Class of protection	A and B				C			All
Type of arrester	X	Y	Z	Total	X	Y	Z	Total
Coils burned out..........	1	3	16	20	5	40	20	65
Transformers put out of commission, but coils O.K.	2	0	3	5	1	22	10	33
Totals...............	3	3	19	25	6	62	30	98

TABLE VI.

RECORD OF TRANSFORMERS BURNED OUT BY LIGHTNING IN 1915, ARRANGED BY STORMS.

Type of arrester		X			Y			Z			Totals			Grand Total
Class of protection		A	B	C	A	B	C	A	B	C	A	B	C	
No. of storm	Date													
1	May 3	0	0	0	0	0	0	0	0	1	0	0	1	1
2.	15*	0	1	6	0	0	4	9	1	3	9	2	13	24
3	June 7	0	0	0	0	0	0	1	0	1	1	0	1	2
4	11	0	0	0	0	0	1	0	1	0	0	1	1	2
5	12	0	0	0	0	0	11	1	0	2	1	0	13	14
6	July 10	0	0	0	0	0	0	0	0	2	0	0	2	2
7	11	0	0	0	0	0	1	0	0	1	0	0	2	2
8	12	0	0	0	0	0	0	1	0	0	1	0	0	1
9	14	1	0	0	1	0	0	0	0	1	2	0	1	3
10	15	0	0	0	0	0	0	0	0	1	0	0	1	1
11	18	0	0	1	0	0	0	0	1	1	0	1	2	3
12	Aug. 14	1	0	0	1	0	7	0	0	0	2	0	7	9
13	16	0	0	0	0	0	27	1	0	11	1	0	38	39
14	23	0	0	0	0	0	2	0	0	0	0	0	2	2
15	Sep. 8	0	0	1	1	0	6	0	1	5	1	1	12	14
16	10	0	0	0	0	0	1	2	0	1	2	0	2	4
	Totals	2	1	8	3	0	60	15	4	30	20	5	98	123

*The two storms occurring on May 15th, one in the early morning and one in the late afternoon, have been classed as one storm, on account of the impossibility of making an accurate separation.

segregated in Tables IX and X so as to show the variation in the percentage of trouble in the transformers supplied by various manufacturers. The percentage figures from Table VIII have been plotted in Fig. 13, and there has been added, for the purpose of comparison, the corresponding information from the records of 1913.

TABLE VII.

RECORD OF TRANSFORMER PRIMARY FUSES BLOWN BY LIGHTNING IN 1915, ARRANGED BY STORMS.

Type of arrester		X			Y			Z			TOTALS			Grand Total
Class of protection		A	B	C	A	B	C	A	B	C	A	B	C	
No. of storm	Date													
1	May 3	2	0	1	3	0	4	1	0	7	6	0	12	18
2	15*	11	0	14	5	0	30	8	1	8	24	1	52	77
3	June 7	0	0	0	0	0	0	1	1	0	1	1	0	2
4	11	1	0	0	0	0	0	0	0	0	1	0	0	1
5	12	3	0	9	8	1	26	10	0	3	21	1	38	60
6	July 10	3	0	0	0	0	16	0	0	1	3	0	17	20
7	11	0	0	1	1	0	3	0	0	2	1	0	6	7
8	12	0	0	0	0	0	7	0	0	1	0	0	8	8
9	14	0	0	1	3	0	0	0	0	0	3	0	1	4
10	15	0	0	0	0	0	0	0	0	0	0	0	0	0
11	18	0	0	1	2	0	0	0	0	3	2	0	4	6
12	Aug. 14	4	0	3	4	1	26	1	0	0	9	1	29	39
13	16	0	0	0	1	0	42	4	2	26	5	2	68	75
14	23	0	1	2	0	0	4	1	0	2	1	1	8	10
15	Sep. 8	2	0	2	3	0	14	3	3	4	8	3	20	31
16	10	0	1	1	5	1	4	7	2	3	12	4	8	24
	TOTALS	26	2	35	35	3	176	27	9	60	97	14	271	382

*The two storms occurring on May 15th, one in the early morning and one in the late afternoon, have been classed as one storm, on account of the impossibility of making an accurate separation.

Fig. 14 shows the ratio of primary fuses blown to transformer burn-outs during the year for each class of protection. The variations in the ratio for all classes of protection are shown in Fig. 15 to which has also been added, for comparison, similar information for 1913.

XVI—COMMENTS ON THE ANALYSIS OF THE RECORDS

In attempting to analyze the records and to discover the funda mental principles of lightning protection, not only is one confronted by records which are incomplete and inaccurate due to the errors which naturally creep into any records that are collected from so many sources, and through so many individuals but there are a large number of variables affecting the amount of trouble due to lightning, which might be roughly outlined as follows:

1. The percentage of terminal boards removed.
2. The ratio of lightning arresters to transformers.

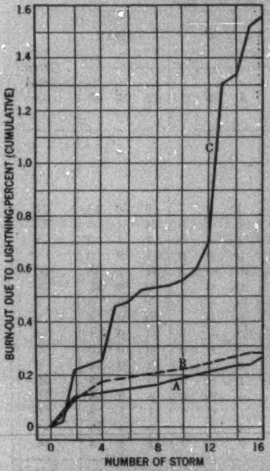


FIG. 11—GRAPHIC LOG OF TRANSFORMERS BURNED OUT BY LIGHTNING IN 1915, SUBDIVIDED BY CLASSES OF PROTECTION

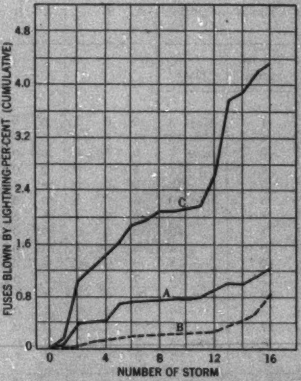


FIG. 12—GRAPHIC LOG OF FUSES BLOWN BY LIGHTNING IN 1915, SUBDIVIDED BY CLASSES OF PROTECTION

3. Location of the lightning arresters, *i.e.*, whether on the line poles or transformer poles.
4. Density of the arresters, *i.e.*, the number per square mile or per mile of line.
5. The maker of the transformer.
6. The variations in the distribution and intensity of the lightning.

In general the variations of the lightning itself overshadow the rest of the variables so that the latter are sometimes quite insignificant in comparison. In other cases the variations in the variables apparently oppose each other, or perhaps act together in such a way that their effect becomes very obscure.

The large variations due to the lightning itself, may be noted in any of the records which give percentage figures for the various numbered areas, and from these records we gather that it is quite unsafe to assume that the record for any particular area correctly represents the average conditions throughout the city. The most representative figures are those which are obtained from the combined experience in a number of areas. In some cases this is not possible, and in those particular cases the attempt to plot the relation between any quantity and the effects of the lightning are quite dissappointing.

TABLE VIII.

RECORD OF TRANSFORMER TROUBLES CAUSED BY LIGHTNING IN 1915, FOR EACH SIZE OF TRANSFORMER

Size kw.	Transformers in service August 1st, 1915.	Burned out		Fuses blown	
		No.	Per cent	No.	Per cent
1	407	7	1.72	22	5.41
1.5	1,090	23	2.11	61	5.59
2	1,103	21	1.90	51	4.61
3	2,381	25	1.05	51	2.14
4	1,149	8	0.70	20	1.74
5	2,075	14	0.67	54	2.60
7.5	2,304	14	0.61	61	2.64
10	1,852	6	0.32	35	1.89
15	1,320	2	0.15	16	1.21
20	648	2	0.31	2	0.31
25	451	0	0	3	0.67
30	186	0	0	1	0.54
40	152	0	0	1	0.66
50	243	1	0.41	4	1.65
75	114	0	0	0	0
100	117	0	0	0	0
150	12	0	0	0	0
250	1	0	0	0	0
TOTALS	15,605	23	0.78	382	2.44

It is also to be noted that in attempting to find the relation between any one variable and the lightning effects, the other variables must for the moment be assumed as constant. The records show that this last assumption is always in error to a greater or less extent. Sometimes the variations from the assumption is not sufficient to seriously affect the records, but in other

TABLE IX.

TRANSFORMER BURNOUTS DUE TO LIGHTNING DURING 1915, FOR EACH SIZE AND MAKE OF TRANSFORMER PER CENT

Maker	A	B	C	D	E	Total
Size kw.						
1	0	1.55	....	....	16.65	1.72
1.5	1.43	1.17	1.40	0	10.48	2.11
2	1.11	1.73	2.61	0	7.41	1.90
3	0.29	0.96	0.97	0	6.06	1.05
4	0	0.65	1.00	6.67	.....	0.70
5	0	0.83	0.46	0	0	0.67
7.5	1.04	0.39	0	0	2.20	0.61
10	0.45	0	1.74	0	0.84	0.32
15	0	0.18	0.72	0	0	0.15
20	1.89	0	0	16.65	0	0.31
25	0	0	0	....	0	0
30	0	0	0	0	0	0
40	0	0	0	0	0	0
50	0	0	0	9.09	0	0
TOTALS	0.51	0.66	0.81	1.47	1.69	0.78

TABLE X.

TRANSFORMER FUSES BLOWN BY LIGHTNING FOR EACH SIZE AND MAKE OF TRANSFORMER DURING 1915

Maker	A	B	C	D	E	Total
Size kw.						
1	12.5	5.5	....	0	0	5.41
1.5	5.7	5.8	4.9	....	4.8	5.59
2	4.5	4.4	7.8	0	0	4.61
3	1.4	2.2	3.5	0	1.0	2.14
4	1.8	1.7	2.0	0	....	1.74
5	3.3	2.3	3.2	0	7.5	2.60
7.5	2.1	2.3	5.6	4.0	2.6	2.64
10	2.3	1.5	4.4	5.0	1.7	1.89
15	1.6	1.3	2.9	0	0	1.21
20	1.9	0.3	0	0	0	0.31
25	0	0.8	0	....	0	0.67
30	0	1.2	0	0	0	0.54
40	0	1.1	0	0	0	0.66
50	0	2.5	0	0	0	1.65
TOTALS	2.34	1.33	3.55	1.47	1.33	2.44

NOTE: The letters used to represent the maker, correspond with those used in Table IX cases the variations are apparently so great that it is quite impossible to draw any conclusions from the results obtained, except in a very general way.

XVII—REDUCTION IN THE RATIO OF PRIMARY FUSES BLOWN TO TRANSFORMERS BURNED OUT

While the number of primary fuses blown and the burnouts due to lightning during the past four years have varied over rather wide limits from year to year as shown in Fig. 3, the ratio between these two quantities during the same period has been decreasing along a very regular curve, indicating the existence of some law or progressive change connecting these two quantities. For the purpose of securing information on this point, Table XI has been prepared showing the ratio in question for the several classes of protection during 1915. This table shows that the ratio is smaller for the class B and C protection than for class A. This ratio, being the larger for the best class

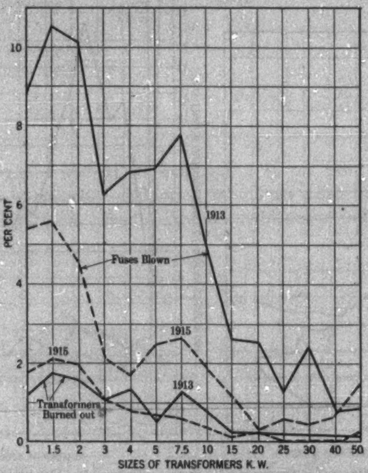


FIG. 13—COMPARATIVE RECORDS OF PRIMARY FUSES BLOWN AND TRANSFORMERS BURNED OUT BY LIGHTNING IN 1913 AND 1915

of protection, indicates that the other variables have a greater effect on this ratio than the lightning arresters.

Fig. 16, showing the reduction in the percentage of terminal boards and in the percentage of fuses blown by lightning, indicates that there must be some close relation between these two quantities as indicated by the fact that the curves are, in general parallel. (In this figure the values for transformers above 15-kw. capacity have been omitted, as not more than four fuses of any of these sizes were blown during the year.) In order to determine the relation between the removal of the terminal boards and the reduction in the fuses blown, these two quantities have been plotted directly in Fig. 17. After making due allowance for the various inaccuracies in the assumptions and conditions, the points from Fig. 16 when plotted in this manner show that the relation between the two quantities is a function represented by a straight line passing through the origin, or in other

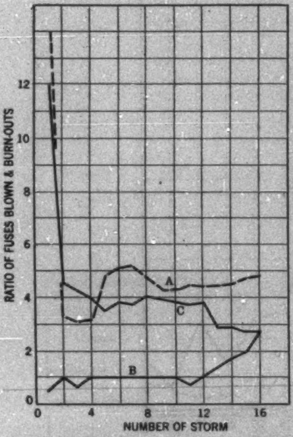


Fig. 14—Diagram Showing Ratio of Fuses Blown to Transformers Burned Out by Lightning in 1915 for Various Classes of Protection

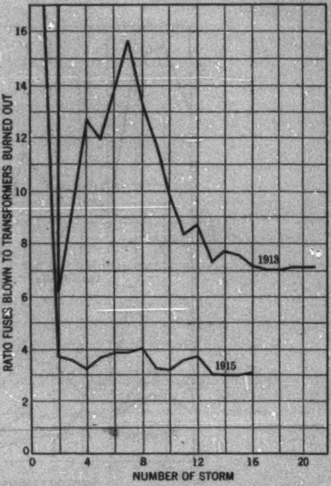


Fig. 15—Diagram Showing Ratio of Primary Fuses Blown to Transformers Burned Out by Lightning in 1913 and 1915

words, that the percentage reduction in fuses blown is directly proportional to the percentage of terminal boards removed.

Upon examining this line more carefully, an apparent inconsistency is noted in that the removal of 30 per cent of the terminal boards caused a reduction of 59 per cent in the fuses blown by lightning. Such a result could occur only if some scheme of selection were practised in the removal of the primary terminal boards, so that the ones most likely to cause trouble were the ones to be removed; but no such scheme of selection has been in use, and instead, all of the transformers passing

TABLE XI.

EFFECT OF CLASS OF PROTECTION ON RATIO OF FUSES BLOWN TO TRANSFORMERS BURNED OUT IN 1915.

Class of protection	A	B	Ratio $\frac{A}{B}$
	Primary fuses blown	Transformers burned out	
A	97	20	4.85
B	14	5	2.80
C	271	98	2.75

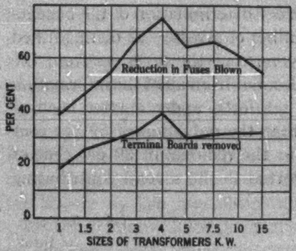


FIG. 16—DIAGRAM SHOWING EFFECT OF REMOVAL OF TERMINAL BOARDS FOR TWO YEARS ON PERCENTAGE OF FUSES BLOWN BY LIGHTNING

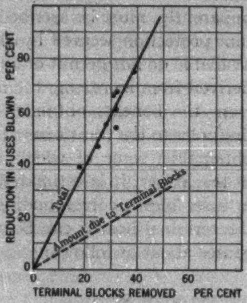


FIG. 17—DIAGRAM SHOWING RELATION BETWEEN REMOVAL OF TERMINAL BOARDS AND REDUCTION IN BLOWING OF PRIMARY FUSES

through the storeroom have had their terminal boards removed before again being sent out on the line.

In the paper by the author read at Pittsfield in 1914, and previously referred to, it was stated that the removal of all of the terminal boards from the transformers in a given area eliminated about 60 per cent of the transformer troubles caused by lightning. Assuming for the moment that this figure is correct, then we might reasonably conclude that the removal of 30 per cent of the terminal boards should reduce the troubles by 30 per cent of 60 per cent, or 18 per cent. The dash line in Fig. 17 shows this value. If we assume that this line is correctly drawn, then the percentage reduction in fuses blown between the dash line and the full line must be due to other causes.

During the same period, that is, between 1913 and 1915, the lightning protection of the system has been improved, (1) by increasing the number of arresters on the line, and (2) by moving the arresters from the line poles to the transformer poles. It is not thought that any of the other changes made during this period could have seriously affected the ratio. The difference between the dash line and the full line on Fig. 17, apparently, must be ascribed to the improvement in the lightning protection secured by the lightning arresters. The records available do not permit of an exact determination of the benefits derived from increasing the number of arresters as distinguished from the benefits obtained by moving the arresters from the line poles to the transformer poles, but from all of the information obtainable, some of which is set forth under a later heading in this paper, it is estimated that the reduction of 59 per cent in fuses blown corresponding to the removal of 30 per cent of the terminal boards can be allotted to the several contributing causes about as follows:

	Per cent	Per cent of total
Removal of terminal boards	18	30
Increasing the ratio of arresters to transformers	10	20
Moving arresters from line poles to transformer poles	31	50
	59	100

If this estimate is approximately correct, it means that the amount of trouble from lightning, on a system with all the terminal boards removed and with lightning arresters equal in number to the transformers and installed on the line poles, would be reduced about one-half by moving the lightning arresters from the line poles to the transformer poles.

A careful investigation was made of transformer fuses blown in 1915, in order to determine how much improvement was due to the removal of the terminal boards only and to the installation of the arresters independent of the removal of terminal boards. If we start with transformers having terminal boards above oil and without lightning arresters on the same pole, then the improvement obtained by each of the several steps, as indicated by our experience in 1915, is as follows:

	Improvement
1. Removal of terminal boards only............	50%
2. Installation of lightning arresters on the transformer poles only........................	85%
3. Removing terminal boards from transformers already protected by an arrester on the same pole............................	30%
4. Removing terminal boards and installing arresters on the same pole................	90%

XVIII—Comparison of Several Classes of Protection

Class A and B protection both include transformers having lightning arresters on the same pole. They differ, however, in that class A transformers are all in a segregated area in which each transformer is similarly protected, while the transformers of the class B protection may be surrounded by other transformers of class C protection, that is, without arresters on the same poles. Fig. 11 indicates that according to the record of burn-outs, class A is appreciably better than class B. Fig. 12, showing the record of fuses blown, indicates that class B is considerably better than class A. This latter difference is probably accounted for largely by the rule above mentioned, according to which transformers above 3-kw. capacity were protected by an arrester on the same pole, while the smaller transformers were not so protected. Class B protection, therefore, consists of a selected lot of transformers from which the smaller, or more vulnerable sizes are largely excluded. This is shown by Table II, which indicates that 21 per cent of the transformers in class B protection were below five kw., while for class A protection this figure was 35 per cent.

If the improvement of class A protection over class B, as indicated in Fig. 11, correctly represents their relative merits, then these conditions must be due to the larger number of arresters per square mile, or per mile of line, for class A protection as compared with class B. A reference to Table I shows that there are about ten times as many transformers per square mile for class A protection as for class B. These figures indicate that the installation of an arrester on a transformer pole does not give perfect or complete protection, but that the protection is considerably improved by other arresters on neighboring poles. This means that widely separated transformers along a long line, or isolated at the end of a line, if supplying important service should be protected by installing other arresters in the vicinity in addition to those on the transformer pole.

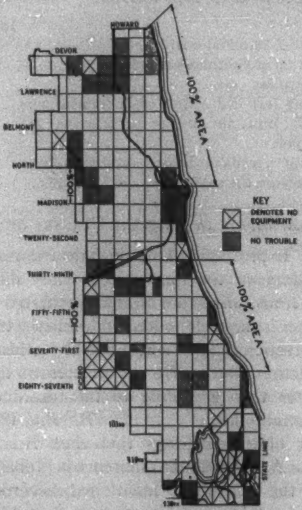

HOWARD
DEVON
LAWRENCE
BELMONT
NORTH
MADISON
TWENTY-SECOND
THIRTY-NINTH
FIFTY-FIFTH
SEVENTY-FIRST
EIGHTY-SEVENTH
CICERO
103rd
119th
138th
STATE LINE
100% AREA
100%
100% AREA
100%
KEY
DENOTES NO EQUIPMENT
NO TROUBLE

FIG. 18—MAP SHOWING SECTIONS (SQUARE MILES) WHICH WERE ENTIRELY FREE FROM LIGHTNING TROUBLES DURING 1915

The figures in Table II for transformers above 15 kw. also show by the large percentage of these transformers the operation of the rules under heading XIII.

It is very evident from Figs. 11 and 12, as well as from several of the tables, that classes A and B protection are both considerably better than class C. Table VIII indicates that the percentage of fuses blown for class A is less than one-third of that of class C, while for the transformer burn-outs the ratio is about one to six.

XIX—ANALYSIS OF CLASS C PROTECTION

As stated earlier in the paper, classes B and C protection cover all of the transformers outside of the 100 per cent areas or class A protection. If the transformers included in class B protection are for the moment ignored then the arresters installed for class B protection can be considered, relative to the class C transformers, as being installed on the line poles.

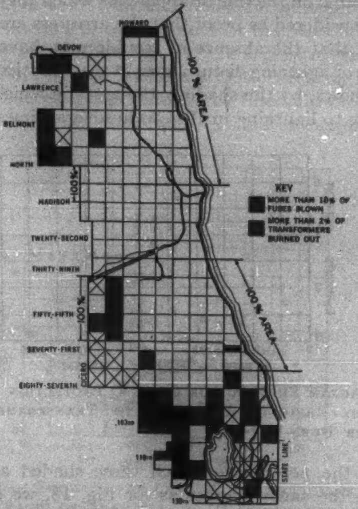

HOWARD
DEVON
LAWRENCE
BELMONT
NORTH
MADISON
100%
TWENTY-SECOND
THIRTY-NINTH
FIFTY-FIFTH
100%
SEVENTY-FIRST
CICERO
EIGHTY-SEVENTH
103rd
119th
130th
STATE LINE
100% AREA
100% AREA
KEY
MORE THAN 10% OF FUSES BLOWN
MORE THAN 2% OF TRANSFORMERS BURNED OUT

FIG. 19—MAP SHOWING SECTIONS (SQUARE MILES) IN WHICH THE TROUBLES FROM LIGHTNING WERE SEVERAL TIMES THE AVERAGE

For the purpose of getting a general view of class C protection, Figs. 18 and 19 have been prepared. The former shows by the shading, with the section (*i.e.* square mile) as a unit, the areas in which there was no transformer trouble caused by lightning during the year 1915. Excluding the sections in which there are no transformers, it is found that within the 100 per cent areas

23 per cent of the total was entirely without trouble, while outside of the 100 per cent areas the corresponding figure was 26 per cent. These figures are so close that one can reasonably conclude that the entire absence of lightning trouble from extended contiguous areas indicates absence of lightning disturbances rather than perfection of the protection. This also means that the fact, that a comparatively few lightning arresters of any particular type have passed through an entire season without any trouble on the line or apparatus which they protected, is not to be considered as proof that the arresters are of value. It is probable that the absence of trouble may have been due to the absence of lightning disturbances at these particular locations.

Fig. 19 shows, by the shading, the areas in which transformer troubles due to lightning in 1915 were several times the average.

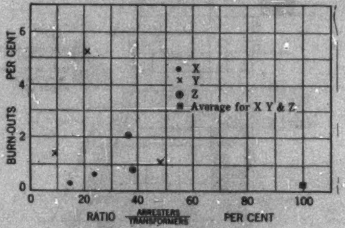


Fig. 20—Diagram Showing for Class C Protection the Relation Between the Ratio of Arresters to Transformers and the Transformer Burn-Outs

Comparing the percentage which these shaded areas bear to the total in the same manner as for Fig. 18, we find that the areas showing the fuses blown in Fig. 9 are 6 per cent and 28 per cent respectively for the class A areas and for the rest of the city. The similar figures for transformers burned out are 13 per cent and 33 per cent respectively. When considered with the results from Fig. 18, these figures appear to indicate that lightning arresters protect the transformers against a large fraction of the lightning strokes, and that the rest of the strokes, which are probably of a very high frequency and large volume, are beyond the capacity of the arrester.

By comparing the shaded areas on Fig. 19 with a map showing the number of transformers in each section, it can be noted that the shaded sections outside the 100 per cent areas are, in general, the sections in which the number of transformers per square mile is small. An attempt has been made to plot a curve showing the variation of lightning trouble with the ratio of arresters to transformers, as shown in Figs. 20 and 21. The points in Fig. 21, showing the fuses blown, almost result in a curve. One point, however, is almost off the scale. This is the result of the storm of August 16th and if this particular storm is eliminated from the record because of its nature, before plotting results, then the storm of May 15th should also be omitted. The latter storm, however, affects other points so that the final result is not materially better than Fig. 21. In a general way, the conclusion can be drawn from this figure, that increasing the number of arresters reduces the percentage of fuses blown; that is, it improves the lightning protection. Taken in conjunction with the previous figure, the points on Fig. 21 appear to indicate that the installation of comparatively few arresters on a line will make an appreciable improvement in the lightning protection.

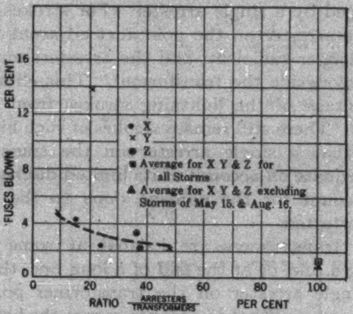


Fig. 21—Diagram Showing for Class C Protection the Relation Between the Ratio of Arresters to Transformers and the Primary Fuses Blown

On Fig. 20 the points are so scattered that it is quite impossible to draw a line which would fairly represent average values. It is probable, however, that a part of this difficulty may be due to differences in the protective values of the several types of arresters.

Taking the several conclusions into consideration, it appears that, starting with the assumptions, (1) that lightning strokes cover a wide range of frequency, and (2) that a lightning arrester acts like a pop-valve rather than like an umbrella, the behavior of the lightning arresters during a thunder storm, may perhaps, be described as follows. Some of the lightning strokes are of comparatively low frequency and moderate volume, so that an arrester placed anywhere along the portion of the line affected by the stroke will protect the transformers. This type of stroke is the only kind that is seriously affected by the old fashioned scheme of scattering a few arresters along the line poles.

For strokes of higher frequency, it becomes necessary to have the arresters nearer the transformers, and this may be accomplished in part by installing an arrester on the pole next adjacent to each transformer. This results in a considerable improvement by the elimination of strokes of moderately high frequency, and also of the lower frequency strokes that are of too great volume to be discharged by a single arrester. For strokes of very high frequency, the arrester on the pole next adjacent to the transformer is no longer sufficient, and the arresters must be placed immediately alongside the transformer. This eliminates a still further percentage of the lightning strokes from the list that cause damage. There still remain strokes of such high frequency and volume that a single arrester on the transformer poles becomes inadequate on account of its limited discharge capacity. This may account for the damage done to the transformers that are so protected.

Where the transformers are located at some considerable distance along a line, or at the end of a long line, the indications are that a single arrester on the transformer pole will again prove inadequate, and that in order to secure the best protection the rules should require, in addition, a certain maximum distance (not yet determined) between arresters, so as to protect against the lightning strokes of moderate frequency and considerable volume, which cannot be discharged by a single arrester and which are apparently a fair proportion of the total number of strokes.

One of the causes of the difficulty in attempting to secure average results from lightning conditions is well illustrated in Fig. 10. Upon making a critical examination of this map it will be noted that within the four sections adjacent to 111th and State Sts., there were five burned out transformers and 24 blown fuses, or a ratio of 1 to 4.8, while in the four square miles adjacent to 95th St. and Ashland Ave., there were 16 burn-outs and

TABLE XII.
SUMMARY OF RESULTS WITH CLASS C PROTECTION. ARRANGED BY AREAS.

Type of arrester	X			Y				Z		
Area No.	2	10	Total	4	11	20+ 21	Total	9+ 12	19	Total
No. of transformers	394	824	1218	1504	746	634	2884	1142	1054	2196
" arresters*	60	198	258	136	358	131	625	436	386	822
Ratio $\frac{\text{arresters}}{\text{transformers}}$ per cent	15.2	24.0	21.2	9.0	48.0	20.6	21.6	38.2	36.6	37.5
Burn-outs No.	1	5	6	21	8	33	62	8	22	30
" per cent	0.25	0.61	0.49	1.40	1.07	5.2	2.1	0.70	2.08	1.37
Fuses blown No.	16	19	35	72	16	88	176	25	35	60
" " per cent	4.1	2.3	2.9	4.8	2.15	13.9	6.1	2.2	3.32	2.74
Transformers below 5 kw. per cent	56	46	49	62	47	76	60	33	71	51

*Same as *B* transformers.

14 blown fuses, or a ratio of 1 to 0.9. At the former location it appears that there was a large number of strokes of lightning of moderate frequency and volume so that only 20 per cent of the total number of troubles resulted in burned out transformers. At the latter location there was apparently a group of very high-frequency discharges of considerable volume as indicated by the fact that over one-half of the transformer troubles resulted in burn-outs.

Similar evidence of erratic behavior of the lightning can be seen in the storm of May 15th, shown in Fig. 9. In this storm it will be noted that several transformers burned out near 55th St. and Crawford Ave., which were several miles distant from any other lightning trouble. The two burn-outs near 63rd St. and Crawford Ave., were on the same pole, one transformer, burning out in the early morning, was replaced by another during the day and was again burned out by lightning during the evening. In this case there was an arrester on the same pole. If one were inclined to draw conclusions from isolated cases, it might be concluded from this particular example that the presence of a lightning arrester on a transformer pole is a hazard.

On Fig. 9 there can also be noted, in the northern part of the city, a large number of fuses blown without any transformer burn-outs in the immediate vicinity. In particular, there is one group of such cases near Western & Lawrence Aves. It would, of course, be very interesting to learn whether this group of primary fuses were all blown by one stroke of lightning, or by a number of successive strokes. Such information is very difficult if not impossible to obtain.

XX—Conclusions

As a result of the experience in 1915, the rule under heading XIII was again altered last December, so as to require the installation of a lightning arrester with each transformer thereafter installed, regardless of its size or use. Later it was also decided to extend this rule to all transformers now installed having the class C protection. This is equivalent to stating that the 100 per cent areas are to be extended so as to cover the entire city. This work is now progressing as fast as the deliveries of lightning arresters will permit, and will probably be completed before the presentation of this paper. These changes in the rules were made on account of the improvement in service, which in the light of experience, might reasonably be expected. The net result of the increase in the number of arresters will be an increase in the annual charges against the system of distribution, and as the saving in repairs to transformers is estimated to be not more than about two-thirds of the interest, depreciation, maintenance, etc., of the arresters, the additional expense must, therefore, be charged against improved service.*

An attempt has been made to set forth, during the discussion of the results, such conclusions as could be most readily drawn from the facts submitted. For convenience, however, these conclusions, together with others that appear to be warranted by experience, may be summarized as follows:

1. The transformer troubles during lightning storms may be reduced: (a) by the removal of the transformer primary terminal boards. (b) By the installation of lightning arresters.

2. Lightning arresters installed on the transformer poles are considerably more effective than if installed on the line poles.

3. When the lightning arresters are confined to the line poles, the protection against lightning is improved by increasing the number of arresters.

4. Whether the lightning arresters are on the line poles or on the transformer poles, the protection appears to be improved by an increase in the number of arresters per square mile or per mile of line.

5. Even in the most severe lightning storms, which apparently cover a given territory quite completely, there will be numerous extended areas within this territory which will be entirely free from lightning disturbances.

6. While a lightning arrester on the same pole with each transformer appears to be quite adequate protection in a region where the transformers are reasonably close together, the protection appears to be inadequate where the transformers are separated by distances ranging above (say) 2000 ft. (609.6 m.)

7. There is no serious difficulty in devising forms of safe construction for installing lightning arresters on the transformer poles. The construction is considerably simplified by the use of self-contained arresters which do not require inspection.

8. The modern types of arresters comply with the specification

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*The calculations on which the above conclusion is based, are given in greater detail in a paper entitled, "Lightning Protection for Transformers on 4000-Volt Distributing Circuits," read before the National Electric Light Association at its convention in Chicago May 22nd to May 26th, 1916.

that a protective device should be less subject to trouble than the apparatus which it protects.

9. The modern types of lightning arresters are so free from trouble that the installation of a fuse in series with the arrester, for the purpose of disconnecting the arrester in case of trouble, is not warranted.

10. Absolute immunity from lightning troubles cannot be secured by an installation of lightning arresters.

11. For the conditions in Chicago the installation of lightning arresters for the protection of transformers is not warranted by the saving in the cost of repairs to transformers, and can be justified only as a means for improving the quality of the service.

12. Great care should be used in attempting to draw general conclusions from the experience obtained from a few arresters, or during a single season or from a limited area.

13. The use of the several schemes for the improvement of the lightning protection that are herein described can reasonably be expected to remove at least 90 per cent of the lightning troubles formerly experienced.

*Presented at the 33d Annual Convention of
the American Institute of Electrical Engineers,
Cleveland, O., June 28, 1916.*

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EXPERIENCE AND RECENT DEVELOPMENTS IN CENTRAL STATION PROTECTIVE FEATURES

BY N. L. POLLARD AND J. T. LAWSON

Abstract of Paper

The protective features described in this paper are some of those now in use on the system of the Public Service Electric Co. which serves a population of about 2,200,000.

The most interesting protective devices and schemes discussed in this paper are as follows:

Aluminum cell arresters; arcing ground suppressor; faulty cable localizer; cable testing; high-potential and high-frequency testing; generator bus connection scheme; exciter connection scheme; reactors; relays; multi-recorder; insulation resistance recorder; air washers; resistance bulbs and thermo-couples; dampers on air-blast transformers; coherer alarm devices; potential indicating devices.

THE ENTIRE territory served by The Public Service Electric Co. comprises three principal divisions; the Northern, Central and Southern, which include the more densely populated sections of the State of New Jersey. Fig. 1 shows a diagram of the transmission system.

The Northern Division consists of eight generating stations having a combined capacity of 148,000 kw. and feeding 33 substations.

The Central Division consists of five generating stations having a combined capacity of 17,800 kw. and feeding 13 substations.

The Southern Division consists of four generating stations having a combined capacity of 32,000 kw. and feeding 17 substations.

In the larger stations, current is generated at 13,200 volts, 3 phase, both 25 and 60 cycles, and in most cases is distributed at that voltage between the various stations and substations, through 260 miles (418.4 km.) of underground cable and 425 miles (683.9 km.) of overhead lines.

In the smaller stations, current is generated at 2400 volts, two-phase, 60 cycles, and distributed locally at that voltage. That part of the current not consumed locally, is stepped up to

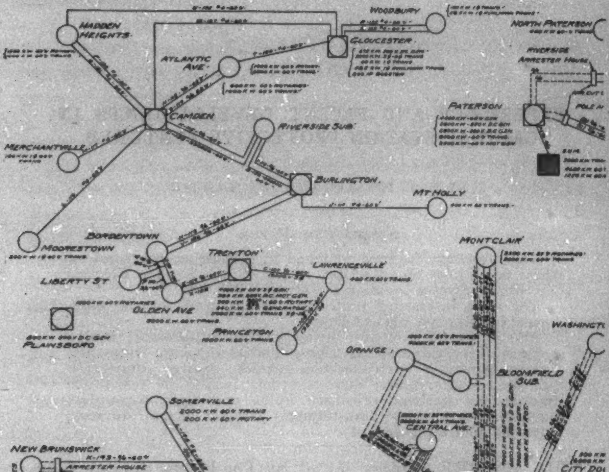
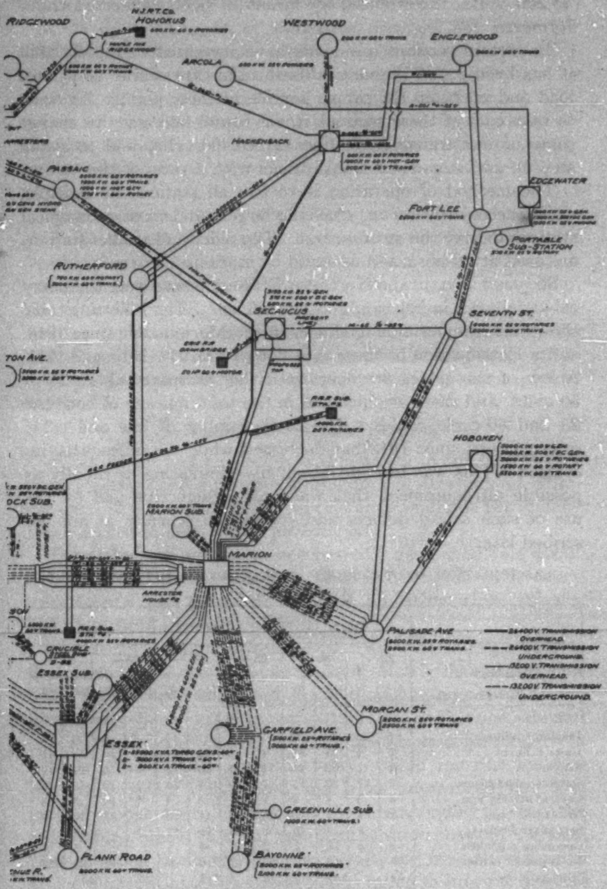

WOODBURY
NORTH PATERSON
HADDEN HEIGHTS
GLOUCESTER
ATLANTIC AVE
RIVERSIDE ARRESTER HOUSE
PATERSON
POLE
CAMDEN
RIVERSIDE SUB
MERCHANTVILLE
BURLINGTON
MT HOLLY
BORDENTOWN
MOORESTOWN
TRENTON
LAWRENCEVILLE
LIBERTY ST
OLDEN AVE
PLAINSBORO
PRINCETON
MONTCLAIR
WASHINGTON
ORANGE
BLOOMFIELD SUB
CENTRAL AVE
SOMERVILLE
2000 K.W. 60~ TRANS
200 K.W. 60~ ROTARY
NEW BRUNSWICK
ARRESTER HOUSE
LINCOLN
800 K.W. 60~ ROTARIES
1500 K.W. 60~ TRANS
CITY DOCK
COAL ST
MILLTOWN
IRVINGTON
CITY DOCK
HARRIS
PLAINFIELD
MECHANIC ST
POLE ARRESTER
RED BANK
NIXON
METUCHEN
CRANFORD
KEASBY
RAHWAY
AVENEL
ELIZABETH SUB
WAVERLY
CARTERET
ELIZABETH
PERTH AMBOY
AVE

FIG. 1—GENERAL TRANSMISSION SYSTEM


N.J.R.T. Co.
HOHOKUS
600 K.W. 60 V ROTARIES
MAPLE AVE RIDGEWOOD
RIDGEWOOD
WESTWOOD
200 K.W. 60 V TRANS.
ENGLEWOOD
ARCOLA
HACKENSACK
ARRESTERS
PASSAIC
FORT LEE
EDGEWATER
PORTABLE SUB-STATION
RUTHERFORD
SECAUCUS
PRESENT LINE
ERIE R.R. DRAWBRIDGE
20 H.P. 60 V MOTOR
PROPOSED TAP
SEVENTH ST.
TON AVE.
P.R.R. SUB. STA. #3
4000 K.W. 25 V ROTARIES
P.S.R. FEEDER
HOBOKEN
3000 K.W. 60 V GEN.
3000 K.W. 300 V. DC GEN.
3000 K.W. 25 V ROTARIES
1500 K.W. 60 V ROTARY
4500 K.W. 60 V TRANS.
OCK SUB.
ARRESTER HOUSE #1
MARION SUB.
MARION
ARRESTER HOUSE #2
P.R.R. SUB. STA. #2
4000 K.W. 25 V ROTARIES
CRUCIBLE STEEL SUB.
ESSEX SUB.
PALISADE AVE
26400 V. TRANSMISSION OVERHEAD.
26400 V. TRANSMISSION UNDERGROUND.
13200 V. TRANSMISSION OVERHEAD.
13200 V. TRANSMISSION UNDERGROUND.
MORGAN ST.
GARFIELD AVE.
ESSEX
2-35000 K.V.A. TURBO GEN.S.-60~
2- 3000 K.V.A. TRANS.-60~
2- 800 K.V.A. TRANS.-60~
GREENVILLE SUB.
1000 K.W. 60 V TRANS.
FLANK ROAD
BAYONNE
ENUE R.

Of the Public Service Electric Company

13,200 volts, three-phase, by means of Scott-connected transformers.

In certain sections our loads have increased so rapidly that it has been found impracticable to take care of any additional load and maintain the proper service at these points. In order to take care of these sections it was found necessary to change some of our transmission lines to 26,400-volts, and to install step-up and step-down transformers with a ratio of two to one.

The method of operation is to run all stations in multiple, which necessarily means that the largest and most economical stations deliver the most output. The older and smaller stations are used at off-peak and as stand-by stations.

Six years ago, in the Northern Division, there were too many cable failures in relation to the mileage. The following table shows the number of shut-downs in the Marion zone since 1913, and a classification of these shut-downs for 1913, 1914, and 1915. A few of the cables are operated either as spare cables, 25 or 60 cyles, and these are included in the total mileage of both the 25 and 60-cycle cables. The total number of line and cable interruptions since 1913 has decreased while the mileage has increased. This was brought about by eliminating as rapidly as possible all equipment that was proved defective and by the use of such safety devices and connection schemes as are described later.

CLASSIFICATION OF TROUBLES RESULTING IN INTERRUPTIONS TO SERVICE

Classification	1913				1914				1915			
	25 ~		60 ~		25 ~		60 ~		25 ~		60 ~	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Insulator failures	12	22	30	20	15	19	14	13	3	6	6	5
Cable failures	2	4	21	14	4	5	12	10	14	26	18	15
Storms	9	17	16	11	11	14	15	13	8	15	22	19
Outside interference	9	17	22	15	7	9	27	24	5	10	19	16
Central station app	3	5	4	3	1	1	5	4	5	10	3	3
Substation app	2	4	7	5	20	26	11	10	12	23	10	8
Secondary feeders	5	9	23	15	8	10	16	14	..	..	6	5
Operating mistakes	2	4	10	7	2	3	4	4	..	..	5	4
No apparent cause	10	18	15	10	10	13	9	8	5	10	25	22
Total failures	54		148		78		113		52		114	
" " per mile	.39		.69		.56		.44		.38		.40	
Miles cable	83		90		83		121		83		141	
Miles overhead	54		123		54		133		54		144	
Total miles	137		213		137		254		137		285	

ALUMINUM CELL ARRESTERS

While the installation of aluminum arresters has made the apparatus trouble disappear almost completely, and as the table shows, the failures of cables have decreased, it has, as might be expected, not given all the desired protection to the cables. The reason for this is probably that the surges on the cables are in the form of distributed charges and the potentials rise locally in the cables entirely beyond the protective influence of the arrester.

Upon analyzing these cable failures, it was noticed that the majority of them were caused by faults to ground which later developed into short circuits. At this time, due consideration was given to the question of grounding the neutral of the system, but after taking all the factors of the problem into account, such as continuity of service etc., the idea of grounding the neutral was abandoned and it was decided that, as far as the system was concerned, the best remedy was the arcing ground suppressor.

ARCING GROUND SUPPRESSOR

An arcing ground suppressor was installed in our largest generating station and numerous aluminum cell arresters on different parts of the system, believing that they would be the remedy best adapted to meet our requirements.

The arcing ground suppressor has now been in service about five years and the records show that it has operated in every case where a fault to ground occurred, by extinguishing the arc, and preventing an interruption to service.

The arcing ground suppressor consists of three single-pole independent motor-operated oil switches, electrically and mechanically interlocked, to prevent more than one operating at the same time. Each switch is connected to ground on one side and to the bus on the other. The suppressor is controlled by a balanced three-phase potential relay, which remains inactive while the system is balanced, but when unbalanced, due to a ground on one phase, it operates the corresponding phase of the suppressor, which, in turn, grounds the same phase of the bus; thus shunting the current and extinguishing the arc. In cases of short circuit, an extra precaution is taken to prevent possible operation of the suppressor by the addition of an overload relay which opens the control circuit of the suppressor.

A more detailed account of the arcing ground suppressor, its action and effect on a transmission system, can be found in a paper written by E. E. F. Creighton and J. T. Whittlesey published in the TRANSACTIONS of the A. I. E. E., Vol. XXXI, 1912, p. 1881.

FAULTY CABLE LOCALIZER

Working in conjunction with the suppressor is a device known as the faulty cable localizer, which serves the purpose of indicating the particular feeder on which an arc to ground occurs.

This device consists of a relay connected in series with the neutral of the feeder current transformers. When a ground occurs, the secondary current of the transformers becomes unbalanced, and causes the relay to operate. This in turn, rings a bell and lights a pilot lamp which indicates the faulty feeder. It takes about 0.15 of a second for the localizer and 0.3 of a second for the suppressor to operate.

There is one record of a 15-minute interruption to the service in the Northern Division caused by a cable end bell short-circuiting on an armature lead of a generator in one of our stations, before the suppressor and localizer were installed. Shortly after the suppressor and localizer were put in service, the same thing occurred again and the situation was handled in such a manner that no one outside of the power station was the wiser. A number of instances are on record where a ground has occurred on substation buses without an interruption to service.

CABLE TESTING

As a further means of reducing our cable troubles to a minimum we made a careful investigation of the possible causes of failure.

For the first few years, all cable was installed by the manufacturer but we finally took over this work ourselves, with the idea of improving the factors entering into cable installation as much as possible.

A thorough study was made as to the best method of making cable joints and particular attention was given to such factors as

1. Favorable weather conditions,
2. Elimination of impurities, air and moisture.
3. Application of insulating varnish between each layer of tape.
4. Careful and even winding of tape.
5. Improving the human element.

Aside from installation precautions, we have made it a practise to inspect cable during the process of manufacture, and to see that our cable specifications are strictly adhered to.

All cables are tested with 26,000-volts for three minutes before putting them in service, but we do not make a practise of testing them periodically. In case there are indications of trouble on a cable while in operation, it is cut out of service, given a test of 26,000 volts for three minutes, and returned to service in case no failure occurs.

In our opinion, a 13,200-volt cable should not be tested at a voltage higher than 26,000, since our experience has shown that too high a testing voltage often weakens the insulation at some point, which weakness finally manifests itself in a complete breakdown, even under normal operating voltage.

High-Potential and High-Frequency Tests

Our line insulators used a number of years ago consisted of many different types, no one type having been standardized. The old insulators not only spilled over during trouble but also became punctured frequently. The insulator creepage surface was then increased and the insulators tested with high-potential 60-cycle current, but without satisfactory results.

About two years ago, we started testing with high-frequency and were soon convinced from the results obtained that the insulators were not capable of standing this test. Various types of insulators were then experimented upon and a design finally adopted having a ratio of puncture to flash-over of about 2 to 1. Now, every insulator before being placed in stock or used on the lines is given a 15-second high-frequency test. Although these insulators are previously tested at 60-cycles, about 2 per cent fail to pass the high-frequency test.

Generator Bus Connection Scheme

Station capacities have increased so rapidly in the last few years that the bus arrangement has become a matter of vital importance in the protection of both apparatus and service. The ideal arrangement is one that secures the greatest amount of protection to the apparatus, and at the same time localizes and minimizes the effect of trouble.

Two years ago, before beginning work on the new Essex power station, a thorough study was made of various bus schemes and after analyzing those used by the large power plants of this country, it was decided that none of them would be satisfactory.

A bus arrangement was then designed which, in our estimation, would approach the nearest to the ideal, and called the "selective" bus scheme, which is shown in Fig. 2.

The considerations that governed in deciding on this bus layout are as follows:

Flexibility
Simplicity
Limitation of abnormally high currents.
Continuity of service.

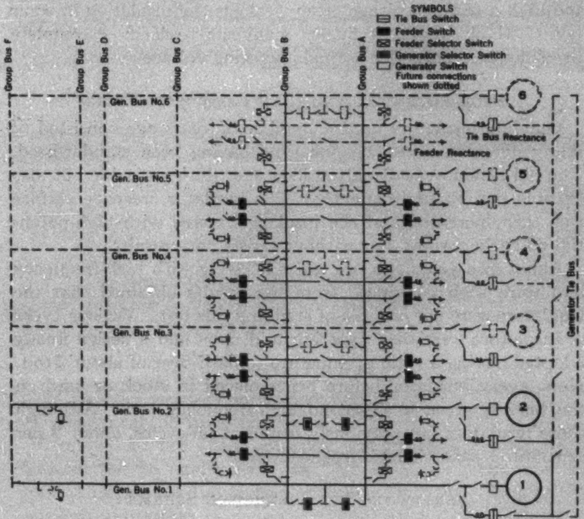

SYMBOLS
Tie Bus Switch
Feeder Switch
Feeder Selector Switch
Generator Selector Switch
Generator Switch
Future connections shown dotted
Group Bus F
Group Bus E
Group Bus D
Group Bus C
Group Bus B
Group Bus A
Gen. Bus No.6
Gen. Bus No.5
Gen. Bus No.4
Gen. Bus No.3
Gen. Bus No.2
Gen. Bus No.1
Tie Bus Reactance
Feeder Reactance
Generator Tie Bus
6
5
4
3
2
1

FIG. 2—SELECTIVE BUS SCHEME

The scheme is made for six generators and consists of one loop tie bus, six generator buses, and six feeder group buses of ten feeders each.

This arrangement of connections is a new application of the old arc board scheme and is the most flexible layout known.

By means of the feeder-selector oil switches, the feeder oil switches can be connected to one or the other of two given group buses; for instance, the twenty feeders on group buses *A* and *B* can all be connected to group bus *A* or group bus *B* or part to each group by twos.

The maximum flexibility in operation is obtained due to the fact that each generator may be connected directly to any part or parts of the load desired.

The generators are connected to a loop tie bus through tie bus reactances and can be operated in parallel at all times, if desired.

EXCITER CONNECTION SCHEME

The exciter connections are fully as important as the main a-c. bus connections, inasmuch as the maintenance of the a-c. generator voltage depends upon the reliability of the excitation. In order to secure a dependable excitation service, several sources of supply should be available. The bus should be so arranged that a failure of one source cannot affect the others, except through its effect momentarily on the main bus voltage. The ultimate exciter system that will be adopted in the Essex station is clearly shown in Fig. 3.

Each generator has a direct-connected exciter, three spare exciters and a battery being available for emergency use. Each source of excitation has its individual bus. In case of voltage failure of one of the direct-connected exciters, a low-voltage relay instantly closes the battery breaker, thus connecting the battery to the affected exciter circuit. Immediately after, the breaker of the exciter in trouble opens, due to reverse current. An emergency exciter may then be started up and paralleled with the battery and the battery disconnected and left ready for emergency service again.

A contact-making voltmeter is provided for maintaining the exciter battery voltage automatically at operating value at every instant.

REACTORS

Bus Tie Reactors. At the present time, generators of such large capacity are being used that it is necessary to protect them from the effects of disastrous short circuits by means of internal or external reactance. Where several generators are operated in parallel, it is essential that bus-tie or bus-section reactors be used in order to prevent the combined capacity of all the generators from feeding into any one point of short circuit. Bus-section reactors will limit the current on any one section but take up valuable space in the bus, complicate the connections, and in cases where parallel feeders are connected to different sections of the bus, it is difficult to obtain balanced currents in these feeders.

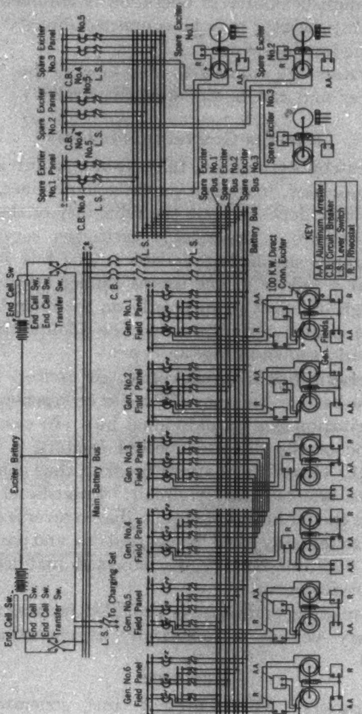

Spare Exciter No.1 Panel
Spare Exciter No.2 Panel
Spare Exciter No.3 Panel
C.B. No.4
No.5
L.S.
Spare Exciter No.1
Spare Exciter No.2
Spare Exciter No.3
Spare Exciter Bus No.1
Spare Exciter Bus No.2
Spare Exciter Bus No.3
Battery Bus
KEY
A.A. Aluminum Arrester
C.B. Circuit Breaker
L.S. Lever Switch
R. Rheostat
100 K.W. Direct Conn. Exciter
Gen. Fields
End Cell Sw.
Transfer Sw.
Exciter Battery
Main Battery Bus
To Charging Set
Gen. No.1 Field Panel
Gen. No.2 Field Panel
Gen. No.3 Field Panel
Gen. No.4 Field Panel
Gen. No.5 Field Panel
Gen. No.6 Field Panel
A.A.
R
Future Installation

FIG. 3—EXCITER SYSTEM, ESSEX POWER STATION

In the selection of reactance coils best adapted to meet our requirements, we were governed by the following factors:

Cost
Low losses
Space occupied

Temperature rise
Ability to stand short circuits
Freedom from inflammable material.

The use of tie-bus reactors has none of the disadvantages of the bus-section reactors, and does limit the amount of

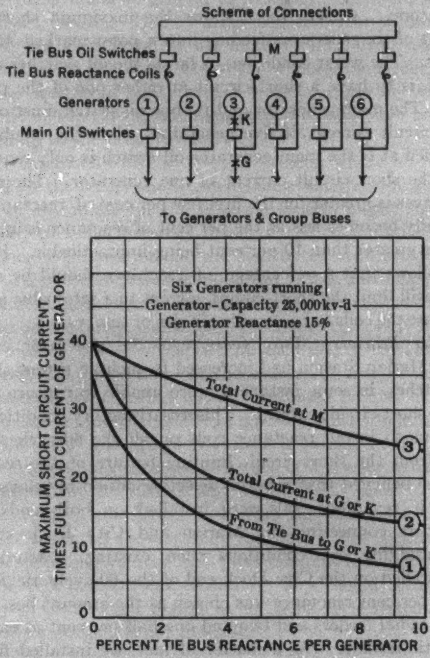


FIG. 4—EFFECT OF TIE BUS REACTANCE SHORT CIRCUIT CURRENT

short-circuit current on any one section to any value desired, depending upon the amount of reactance used. For this reason, tie-bus reactors will be used, connected as shown in Fig. 4.

The curves in this figure show the effect of tie-bus reactance on short-circuit currents; assuming that short circuits occur at the points *G*, *K* and *M*. The per cent tie-bus reactance per

ol. 35
916

generator is plotted against the maximum short-circuit current times full-load current of generators. Assuming that a short circuit occurs at points marked *G* or *K* on generator bus No. 3, the maximum short-circuit current flowing into either of these points from the other five generators is shown by curve No. 1. Curve No. 2 shows the total short-circuit current of all six generators. Curve No. 3 shows the maximum short-circuit current of six generators feeding into a point marked *M* on the tie bus. The worst condition, as far as the oil switches are concerned, is to have a short-circuit at either one of the points *G* or *K*. The main generator and tie-bus oil switch must open the short-circuit current of five generators when the trouble is at *K*; when at *G* the main generator oil switch is only required to open the short-circuit current of one generator. The slope of the curves is greater for the first few per cent of reactance, and gradually becomes less as the per cent of reactance is increased; a value greater than 10 per cent being impracticable. It therefore follows that a percentage of reactance should be selected which will limit the short-circuit current to a safe value and still not cause the coils to be excessive in size or cost.

Feeder Reactors. Two years ago the generator capacity in our Marion Station had increased to such an extent that the oil switches, in some instances, were unable to rupture the excessive short-circuit current. This unsatisfactory condition compelled us to install reactance coils on all the 60-cycle feeders. Aside from the short-circuit limiting feature of the reactance coils, we believed that a better selective action of relays would result, if reactance coils were installed on both ends of the tie feeders connecting the Marion and City Dock stations. After studying the conditions then existing, reactors were also installed on the City Dock end of the 60-cycle tie feeders.

Five per cent reactance was chosen as the amount best suited for the radial feeders and two and one-half per cent at each end of the tie feeders. (As a matter of fact, we installed five per cent reactance coils and used the two and one-half per cent taps.) There were at this time, seven tie feeders between Marion and City Dock and five or six of these operated in parallel at all times. Each feeder consisted of 2.5 miles (4 km.) of cable at the City Dock end, three miles (4.8 km.) of aerial line and one-half mile (0.8 km.) of cable at the Marion end.

If a fault occurred on one feeder there would be 2.5 per cent reactance between either station bus and the fault and an additional 5 per cent reactance between the unaffected tie feeders and the faulty one. As anticipated, this arrangement gave the very best selective action of our relays in case of trouble.

About one year after the installation of the reactance coils, the tabulated records of failures on tie feeders showed that instead of being faults to ground as formerly, they were in most cases, short circuits. Shortly after this, five sets of aluminum cell arresters were installed 2.5 miles (4 km.) from the City Dock station at the point where the underground cables connected to the aerial lines, with a hope of relieving the local potentials in the cables, but satisfactory results have not been obtained up to the present time.

By a comparison with the 25-cycle system, where no reactors are used on the feeders, it seems evident that the change in the nature of the faults on the 60-cycle system might surely be attributed to some unknown result of the combination of the inductance of the reactor and the distributed capacitance of the cable. To overcome rises of potential at the terminals of the concentrated inductance in the reactors, aluminum arresters were installed on the buses, which, with the arresters already installed on the feeders, placed protection on each side of the reactance. Even with this protection, all the sources of trouble have not been reached, as indicated by the continued failures of cables, and two cases of internal failure of reactors which might properly be attributed to a local rise of voltage internally in the reactor.

It is evident that these troubles are of a deeper nature than would appear on the surface and we are laying plans to make a further study of the surges both from the standpoint of localization of potential and natural frequency.

It seems proper to attribute these troubles to surges. If the troubles were due to weak insulation, they should occur as frequently on the 25-cycle system as on the 60-cycle system, which, as already recorded, is not the case.

RELAYS

During the early days of the electrical industry more attention was given to the protection of apparatus than to maintenance of service and therefore, the aim of the operating man was to remove the short circuit as quickly as possible.

In short, the old idea of protection was one of adjusting relays and circuit breakers to protect apparatus against overloads.

Later, with the improvement of station apparatus and its ability to withstand short circuits, the thought gradually took root that the function of the relay should be primarily to protect against interruption of service to the customer. The result is that the modern idea with reference to relays, is to insure continuity of service. It is only in recent years that this idea has developed and central-station men today do not fear breakdowns in apparatus as much as service interruptions.

Carrying out the idea of service protection, operating companies of late years have gone to considerable expense in electrical features related to the transmission system. The best insurance against interruptions has demanded the use of duplicate feeders over more than one route, such as by means of tie lines, parallel feeders, ring connected feeders, etc. This means a larger and more complicated system, an increase in liability of breakdowns, and therefore a more serious problem as far as relay protection is concerned.

It is obvious, that practically all interruptions in a transmission system will be minimized if faults are easily and quickly removed before they have had time to cause serious trouble.

In order to determine the proper setting of instantaneous overload, inverse-time-limit and inverse-definite-time-limit relays which are more commonly used on a system of distribution, it is necessary to know the characteristics of the system as well as the characteristics of the generators, automatic apparatus, circuit breakers, regulators, etc., before anything can be done along these lines, and before the time elements of relays can be adjusted, the following information is necessary:

1. The instantaneous short-circuit value of current through each conductor to which the relays may be applied.
2. The sustained short-circuit value of current through each conductor.
3. The time in changing from 1 to 2.
4. The time required for various automatic circuit breakers to open the circuit after application of current through the trip coils.
5. The safe current-opening characteristics of various circuit breakers.
6. The time characteristics of the various relays.
7. The probability and amount of flow of energy in the case of circuits operating in parallel.

If these seven items were known with any degree of accuracy, it would enable one to accurately set relays, but as a matter of fact, it is almost a physical impossibility to arrive at these seven conclusions with any degree of certainty. For instance, the values of short circuits depend particularly upon the characteristics of the generators and also upon the impedance of the circuit to the point to which the relays are connected. The further the point of the short circuit from the generator, the less will be the difference between instantaneous and sustained short circuits, or between item 1 and item 2, providing the same apparatus is included between the short-circuit point in question and the generator.

Again, operating companies whose growth extends over a period of years, must necessarily operate generators of different internal characteristics. For this reason, the results obtained from setting a relay for values 1 and 2 for a machine purchased several years ago, will not be the same for a generator installed recently.

Assuming for the moment that the seven items listed are known and an attempt is made to accurately time relays for selective action, the accuracy of current values required to trip a relay can be left as a matter of small concern, for when a short circuit occurs, the current setting of relays is usually exceeded by at least several hundred per cent. This applies equally well to inverse-time or definite-time relays. It is an impossibility to get selective setting with the inverse-time-limit relay because it has the unfortunate characteristic of being instantaneous with a heavy overload. This characteristic prevents the use of this type of relay for selective action because a short circuit of sufficient magnitude will cause all the relays from the fault to the source of supply to become instantaneous, and thus any or all of the relays are liable to trip out instead of only the ones nearest the fault.

Better results can be obtained by the use of an inverse-definite-time-limit relay, the time setting of which depends upon the damping action of a permanent magnet on an aluminum disk, giving as great a degree of accuracy as can be obtained in the calibration of watt-hour meters used in connection with a torque compensator.

This type of relay is more accurate and allows closer setting than any other type, and when once set, remains the same, but in an extensive system, the results obtained from its use are nevertheless disappointing. The reason for this is simple, when it is considered that the time interval between successive circuit breakers should be equal to the time taken for the circuit breaker to open its arc, plus a margin of safety to include variation, and if there are several feeder sections in series and the trouble should be near the generating end, the short circuit may not be cleared for several seconds, which means, of course, a loss of all synchronous load on the system, or in other words, a complete interruption to the service.

From the foregoing, it can be seen that irrespective of the character of the distribution system, it is practically impossible to isolate faulty cables or lines by the relays most commonly used, and therefore the records of most operating companies show that faulty feeders usually interrupt a large area and a great many more consumers than is necessary.

With the relays more commonly used, the most satisfactory results are obtained by using them with a radial distribution system; or, in other words, most operating companies get the best results by adapting their systems to meet the faults in the relay rather than design a relay for a minimum cable outlay.

A well designed transmission system is one which has the following characteristics.

1. Safety in operation for employees and the general public;
2. Suitability of supply for the purpose required;
3. Freedom from interruption.

Therefore, the question resolves itself into one of design, as has been shown.

Failure of supply is usually caused by breakdown of transmission and the primary precaution is therefore careful attention to design, manufacture and maintenance of the various parts of the system, but since no apparatus can be made absolutely immune from breakdown or external damage, the secondary precaution is to make arrangements so that the effects of a breakdown to any part of the system are localized as much as possible.

In some cases, such precautions may mean increased capital cost, but undoubtedly result in a net economy if a broad view is taken.

Fortunately, however, well designed apparatus does not necestarily cost more than badly designed apparatus and it is possible to cheapen the system by closer localization of breakdowns.

Balanced Selective Relay. In connection with the seven tie feeders between City Dock and Marion, mentioned elsewhere in this paper, so much trouble was experienced due to the lack of a selective action of the relays, that a new type of relay known as the "balanced selective relay" was finally installed at each end of these feeders.

The relay coils are connected in series with current transformers of the tie lines. This causes the current in each coil to be proportional to the current in the cable to which it is connected.

Only a single phase of each cable is taken care of by a single relay and there are as many coils on the relay as there are cables. For instance, with seven cables on a three-phase system there are three relays with seven coils per relay.

Each coil on each relay is mechanically balanced against each other coil. The effect of this is that any strong coil can overcome any weak coil. In case a short circuit occurs on one cable, the current in the faulty cable will of course be greater than the current in any other cable.

Therefore, the coil connected to the current transformer on the faulty cable will have the strongest pull and will close the tripping circuit of this oil switch.

However, if none of the parallel cables are short-circuited, but trouble occurs on some radial cable, the relay will remain balanced and none of the good cables will be erroneously tripped out. The relays operate simultaneously at both ends of a faulty cable and their operation is not affected by fluctuations in voltage due to trouble or change of phase angle between voltage and current. With this particular type of relay, it is necessary to have not less than three feeders in service, in order to secure perfect operation under all conditions. It should be further borne in mind that reactance coils are installed on both ends of the tie feeders in order to secure the best selective action of the relays. It is questionable whether the relays would operate as satisfactorily in all cases without the aid of these coils. The successful operation of these relays is limited to three or more feeders, therefore, they cannot be used on other parts of our system where there are but two parallel cables between stations.

Since the installation of the balanced selective relays, we have had no case of cable failure on the tie feeders where the relays have not operated properly and there have been more than fifty cases of trouble.

Our operating conditions are such that at times there are but two tie feeders in service, therefore on these occasions it is necessary to disconnect the balanced selective relays and depend on overload protection.

Judging from past experience with different types of relays, a pilot wire relay would seem to be the best one to adopt if it were not for the trouble and expense entailed by the necessity of the pilot wires. Therefore, some scheme based on the pilot wire principle, having all the advantages and none of its disadvantages would be an ideal one for our interconnected system.

Our investigation shows that the nearest substitute for the pilot-wire scheme and one that has practically all the advantages is the split-conductor principle. During the coming year we expect to make several installations of this character.

MULTI-RECORDER

The multi-recorder is a device for recording the time to the fraction of a second of the sequence of action of oil switches, circuit breakers, potential indicating devices and aluminum cell arresters. A record of this kind is invaluable to the station man in analyzing troubles or ordinary switching changes.

In order to have complete information on the performance of station apparatus under all conditions, it is highly desirable to have records of the closing and opening of circuit breakers, operation of lightning arresters, appearance and duration of high voltage in the lines and the occurrence of grounds and short circuits.

At the time of writing this paper the installation of the multi-recorder is not complete, therefore we are unable to give any actual operating experience with this instrument.

INSULATION RESISTANCE RECORDER

The insulation resistance recorder is an instrument which gives a daily graphic record of the insulation resistance of the system. The results obtained so far from the use of this instrument have been rather disappointing, due to the fact that there are so many old insulators of different insulation characteristics. When the insulators are all changed so that they will have the same characteristics throughout the system, we can, by establishing a point on the chart which might be called "dangerous," but which is well above the breakdown point, give the operator an opportunity to report when the insulation of the system reaches this value. By isolating the transmission circuits one at a time, the line in question can be removed from the system and later by high-potential testing or other methods, the bad insulators can be located and removed from the line.

In using this instrument on lines where the insulators have been standardized, very good results have been obtained. Its use has also shown the need of increasing the insulating qualities of porcelain, which is something that we did not know before.

AIR WASHER

The capacity of a generator is directly dependent upon its temperature. In order to keep its temperature as low as possible, it must be supplied with a sufficient amount of clean, cool humidified air.

The specific heat of air being low, it is necessary that it be humidified in order to increase its heat carrying qualities sufficiently. It is also necessary that the air be free from impurities in order to prevent a partial or complete closing of the machine ventilating ducts.

A well designed air washer will satisfy all the requirements mentioned above.

Air washers are used in connection with our largest turbo-generators and our experience leads us to believe that their use is almost a necessity; particularly where the conditions are such that the air contains a great many impurities. If an air washer is not used, it is necessary to remove the rotor of a machine periodically and clean the ventilating ducts or in time they will become so clogged with refuse that over heating will result and a burn-out occur.

Where large air-blast transformers are used and the air conditions are not satisfactory, it would, in our opinion, be advisable to install an air washer.

RESISTANCE BULBS AND THERMO-COUPLES

For several years it was our practise to install resistance bulbs in the windings of the largest turbo-generators and synchronous motor-generator sets, in order to know at all times the temperature of these machines. The results obtained by their use so far have not met with expectations.

The resistance bulbs furnished to-day are somewhat more substantial than the earlier type but are still too frail to stand much hard usage. In the windings of our more recent motor-generator sets thermo-couples have been installed which we believe, will give better service than resistance bulbs, as they are less liable to mechanical injury.

The temperature indicator has been found very useful in determining when a machine needs a thorough cleaning. Thus, a possible burnout is prevented which otherwise could not be foretold.

It is our opinion that wherever possible thermo-couples should be installed at the hottest points in the windings of all large generators or motors.

DAMPERS ON AIR-BLAST TRANSFORMERS

In most of our stations where air-blast transformers are installed a common air chamber is utilized for all the transformers and we have found this method of air supply more economical than to use a separate and independent blower for each transformer. Each transformer is equipped with a top and bottom air damper so that in case of fire in the transformer, the dampers may be closed, thus shutting off the air supply and smothering the fire.

We strongly recommend top and bottom dampers on all air-blast transformers especially where a common air chamber is used. If the transformers are not equipped with both top and bottom dampers and a fire starts in one of the transformers, it is necessary to cut off the entire air supply for a considerable time depending upon how long it takes to put out the fire. This might compel the station man to disconnect the other transformers from the service; thus resulting in a complete interruption.

COHERER ALARM DEVICE

This device is used to register predetermined voltage rises on the transmission line itself, across reactance coils or on aluminum cell lightning arresters. In order to get a permanent record of its action, it can be connected to a relay which will make a record on a multi-recorder. This device has been found very convenient to register the discharges of our aluminum cell lightning arresters.

Previous to the installation of this device, it had been the custom to install with each aluminum cell arrester a discharge recorder which has a continuously moving paper punctured by the discharges. We finally came to the conclusion that while these recorders gave us much desired information, the continual replacement of paper record rolls was expensive and troublesome.

POTENTIAL INDICATING DEVICES

Electrostatic potential indicating devices are used to indicate potential on feeder circuits. The instrument is connected to the middle point of two strain insulators in series, which are connected between each live wire and the ground. The displacement current through the insulators is sufficient to operate the instrument.

Another method of obtaining the voltage indications is to install potential transformers whose secondaries are connected to indicating lamps or voltmeters. However, this means is rather expensive and the required space for potential transformers is not always available.

It would therefore seem that the potential indicating device now on the market might fill a long felt want.

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PROTECTION OF HIGH-VOLTAGE DISTRIBUTION SYSTEMS BY ISOLATING TRANSFORMERS

BY O. O. RIDER

ABSTRACT OF PAPER

This paper calls attention to the practicability of localizing line disturbances by means of transformers. Application is made to high-voltage distribution systems serving the rural communities which results in an inter-connected net work of overhead lines.

IN THE generation, transmission and distribution of electricity there is growing the application of intermediate voltages for the supply of energy to the smaller communities and isolated industrial centers, forming a net-work of high-voltage distribution with characteristics in operation and maintenance that present new problems and require plans for protection differing from those on the low-voltage system used in urban distribution. This development applies more particularly in those sections of the country where the population is generally distributed, such as found in the Middle West.

In choosing an electrical pressure for this work, 33,000 volts has been found to be the highest practicable voltage for pin-type construction, and at the same time a voltage sufficiently low from which small amounts of power can be supplied economically to meet the growing commercial needs. It also appears that a system operating at this voltage is the most suitable intermediate step between very high voltages for delivery of large blocks of power over long distance, and the low-voltage system ordinarily used for distribution in the larger cities.

In the operation of such a system one requirement is at all times preeminent; namely, supplying continuous service over three wires. The non-grounded neutral system is used which permits service being maintained under conditions of accidental ground on one phase. This greatly lessens the chances of interruption by short circuit but, as is well-known, it produces more surges for a longer time during an arcing ground than the grounded-neutral system. Delta connection of transformers is used.

The chief aim of this paper is to call attention to the improved operation obtained from isolating transformers on a non-grounded neutral system. Other attending factors affecting continuity of service are important and are receiving careful attention, but are not within the scope of this article.

LOCALIZATION OF ABNORMAL CONDITIONS

The localization of disturbances caused by single-phase accidental grounds is a matter of great concern, especially in high-voltage systems which extend over a large territory. A single defective insulator which grounds a phase affects the entire system which is metallically interconnected. Small or local electric storms often develop in one section and cause this hazard to service in every other section. When the storm is general the entire system is subjected to these abnormal conditions from the time the storm enters the zone of electrical supply until it passes the remote sections supplied from branch lines. The troubles are multiplied accordingly.

In the growth of these large interurban systems small power plants are sometimes connected where the insulation of the line is not up to the highest standard, due to one cause or another. Also, where systems are connected together for interchange of power, the possibility of trouble from accidental arcing ground is multiplied by this extension of territory covered by the two systems. In many such cases it is undesirable to use automatic circuit breakers at the connecting points to disconnect the power when the trouble is due only to unbalanced electrostatic conditions of the phases.

In these cases isolating transformers between the systems can be advantageously used. These transformers may be either 1 to 1 ratio or they may step down the power to a lower distributing voltage and up again to the transmission voltage, according to the attending conditions. It is desirable, of course, to locate these stations where local distributing service is required. Where a section is to be isolated by this means an added advantage comes in the use of standard regulators for the maintenance of voltage. This plan of regulation will be found to care for voltage conditions at intermediate points and eliminates the necessity of supplying a great number of regulators for the small communities

With these isolating transformers the disturbance of an accidental arcing ground on one section is confined entirely to that section, and still power is transmitted without interference to and from all other sections as under normal conditions.

On each section where an accidental arcing ground takes place the proper protective devices should be used to protect from abnormal voltages. The arcing ground suppressor has been recommended and used. It is not the object of this article to treat these details but simply to record the successful use of the isolating transformer which limits the disturbances to one part of a large system.

DISCUSSION ON "STUDIES IN LIGHTNING PROTECTION ON 4000-VOLT CIRCUITS" (ROPER), "EXPERIENCE AND RECENT DEVELOPMENTS IN CENTRAL STATION PROTECTIVE FEATURES" (POLLARD-LAWSON), "PROTECTION OF HIGH-VOLTAGE DISTRIBUTION SYSTEMS BY ISOLATING TRANSFORMERS" (RIDER), CLEVELAND, OHIO, JUNE 28, 1916.

E. E. F. Creighton: Of Mr. Roper's paper I will say, first, that I think it is a piece of scientific work on a magnificent scale of very great value to the electrical industry. It differs from most of the work, in that it is finished. The whole electrical industry is benefited, new principles have been proved and some principles have been disproved and discarded. There will be a chance to get better service on the part of those who wish it, and better lightning arresters. From my own standpoint I wish to acknowledge a great benefit derived from Mr. Roper's work in that it made possible to choose between several factors of design of lightning arresters, and thereby improved the product for everybody.

Apparently, from the way in which Mr. Roper has presented this paper, it was a very simple affair, but I assure you that the thousands of data which he has collected were in a very chaotic condition, and it required the highest sort of analysis in order to bring some sort of order out of this chaos. All sorts of antagonistic results were obtained—they are all simple enough now after Mr. Roper has analyzed them and told us why they are antagonistic, and he has been able by that method to discard certain parts and draw proper inferences from other parts.

I want to pass on now to the other papers, not as a discussion, but simply to point out certain factors. Take the next paper by Mr. Pollard and Mr. Lawson—this is a paper of a different character. It is a record of progress with new apparatus. The modest presentation of the subject gives an inadequate idea of its importance.

It seems to me a very good time to bring out the importance of the arcing ground suppressor in the problem of grounding the neutral. This discussion, by silence, yesterday, related to one of the very big interests, the telephone interests, and the possibility of interference between the power circuits and the telephone circuits. The interference, unfortunately, is all in one direction, since the telephone circuits have such a tiny amount of power they cannot in any way interfere with the power circuit.

These are two big public service interests in which we are all interested and which we want to see successful, and this problem is not one for the lawyers, but one for the engineers. If the engineers cannot get together and decide what can be done to minimize the effects of interference, the law court is a poor place to go, and the spirit which has been manifested on the two sides of this particular case—I was able to see it because I was brought in as a third party in the discussion of the value of the arcing ground suppressor in avoiding interference—gives hope that this interference may be eliminated in the future. There were cases of interference where the telephone girls received very bad shocks from the heavy grounds that were induced in the telephone line, and we were looking for some method of avoiding them.

The greatest cause of interference and the widest spread of interference between power lines and telephone lines is due to electromagnetic induction. Electrostatic induction is very bad in the case of a telephone line being near the power line, for example, if it is placed underneath or on the same pole with the power circuit. However, by placing the telephone line on adjacent right of way, the electrostatic troubles are reduced to a negligible value which the telephone company can take care of without trouble. When, however, we take into account the electromagnetic troubles, it becomes almost impossible to prevent interference. Take this one case of the Public Service Electric Company where the grounding current for the total system is only 60 amperes. The radius or distance over which 60 amperes will influence the parallel telephone lines is rather small. By grounding the neutral, however, that 60 amperes is turned into several thousand amperes, and the distance over which the electromagnetic force will influence the telephone lines is greatly increased.

One of the strongest factors in maintaining a non-grounded neutral system is by the use of the arcing ground suppressor, and if Mr. Osgood should speak on the subject, he could tell you a lot concerning the studies which they have made relative to the interference, and the conclusions they have come to regarding the use of the non-grounded neutral.

The suspension insulator problem is one which will probably not be solved for some time to come. I wish I had the time to note the relations of these big corporations to the solution of the problem. In the case of the Commonwealth Edison Company it takes a broad spirit to come to the conclusion that Mr. Roper gives in his paper—that with all the work that was done, that with all the thousands of dollars that were spent, the direct gain in the saving of dollars and cents was nil. The whole thing turns on the point that it gives better service. In the same way with regard to the investigations of the Public Service Corporation of New Jersey—the service has stood above everything else.

When we come to the insulator problem, we have a number of comparatively small companies building insulators and reducing the price of the insulators at a time when a big corporation would have increased the price and put the difference into experimental work. There is no saving today in having a cheap insulator. If the cost of the insulator could be increased fifty per cent, and it would do away with the line troubles, it would be a great saving to the transmission engineer, but it seems impossible for the smaller concerns to get together and carry on such an investigation.

C. P. Steinmetz: Reverting for a moment to the individual papers, it is interesting and significant in Mr. Roper's paper to note the conclusion that although 100 per cent protection is not warranted because the cost of perfect protection is somewhat greater than the cost of repairing damage to transformers resulting from less perfect protection, nevertheless, he introduced 100 per cent protection as quickly as possible because reliability is the all-important question. Unfortunately, it is not every electrical system which takes that attitude; it is far from being the case. There are, indeed, many that have not reached the high standard which the world will demand in the future, but those which have adopted this standard include I may say, practically all of those operating systems that are the descendants of the old Edison three-wire d-c. system.

In Mr. Rider's paper is another interesting and significant statement, namely, that the non-grounded delta system has been preferred. Now, there are many engineers, especially in the West, whose experience has been different, and who from their experience prefer a grounded Y system of transmission, but the explanation of this apparent difference of opinion is contained in Mr. Rider's paper in the statement that one requirement is at all times pre-eminent, namely, supplying continuous service over the three wires. It is brought out, as sharply as it can be, that the relation between the isolated delta and the grounded Y is that of reliability of service as compared with cheapness, and where it is desired, at the least investment, to get some kind of service, there the grounded wire has the advantage, because with the line insulated to a lesser degree this system gives less trouble. But where reliability first is the predominant feature, as it must be in those great systems which really desire to change the statement, that the good and old reliable is not the electric light, but the tallow candle, there the isolated delta is used.

The pre-eminent importance of a high degree of reliability is present throughout all the arguments of the three papers, and is substantiated to some extent, by experience in establishing and maintaining such reliability. It is in reality a great social problem involving the organizing of a universal power distribution and supply by electricity, different phases of which are severally dealt with in these papers.

Mr. Rider's paper deals with one phase of it, that of country distribution; Mr. Roper's paper deals with another phase of it, that of city distribution, and the third paper deals with station control and system control. But when electrical engineering enters the field of taking over the universal power supply of the community, of the nation, they must then go beyond the old conception of trying to organize so as, with the minimum possible investment, to get the maximum immediate returns, because as soon as they undertake a universal problem, a social duty also devolves upon them, the duty of giving satisfaction to all.

Then also comes in the problem of not interfering with other lines, with the telephone, etc., and in taking all those precautions that will safeguard life and at the same time give maximum reliability, in short, a conception of organizing the system so that it will be a benefit to all and a harm to none. That is the fundamental requirement which is before us, and which must be the universal conception and practise before we can expect electric power to be used as the universal agent of the world's energy supply.

In closing, I wish to add only one feature to the general discussion dealing with protective devices, provided against abnormal voltage, abnormal current, abnormal frequency, etc., and that is, to mention a further protection against troubles which are encountered, not in the experience with those systems which have been considered today, but rather in other systems, in smaller systems, where economy of installation has predominated, and economy of operation has followed. The troubles to which I refer, the sources of many mysterious interferences with reliability, are carelessness and dirt.

A switch is opened by some assistant operator by mistake, and is immediately thrown in again, before this is noticed. The synchronous apparatus has fallen out of step, or otherwise flashes over, and a mysterious accident has to be investigated by writing theories on high frequency, etc. Or a high-voltage switch bushing, gradually becoming covered with dust and dirt, is located near a window; the window is left open admitting moisture laden air, which condenses on the dirt and a flash-over results; the lightning arrester does not discharge, and the transformer is burned up by a short circuit. Then an investigation shows by factory test that it requires more than three times normal voltage to flash-over that bushing, hence, there was high voltage present. The lightning arrester did not discharge, although only a short distance away, and that means that this high voltage was of such extremely high frequency as not to reach and discharge from the lightning arrester. It results often in a general lack of confidence and uneasiness on the part of the operating staff.

Such things can be avoided only by automatic recording devices which would have shown there was no abnormal voltage and no high frequency present, that the accident started with a short circuit at the bushing, and therefore the bushing was in such condition that normal voltage and normal frequency went over it. In the other instance that I mentioned, the automatic recording device showed that the switch was opened and immediately thrown in again, of which operation there was no record in the station report.

These instances illustrate what I want to bring out—I do not wish to say there are no such things as high-frequency disturbances, excessive voltage, etc. They are often present, and have shown themselves over and over again. They are the most frequent and serious causes of trouble in existence, but do not let us always jump to the conclusion that every trouble is due to some mysterious phenomenon; let us also keep in consideration of the fact that the human element and the fallibility of human nature are involved, which matter is a very frequent cause of trouble, against which there is no remedy except by the use of automatic devices, that are not susceptible to human frailties or neglect, and will not forget to record immaterial incidents.

P. H. Chase: In Messrs. Pollard and Lawson's paper a brief mention is made of the split or divided-conductor principle in its relation to ideal relay protection of transmission circuits. I wish to bring out a few points in connection with the methods used in the application of this principle.

What may be called the individual differential or balance method has been used for some time for the protection of transformers, generators and cables in order to secure perfect selective disconnection of faulty equipment from the system, in the minimum time. This is accomplished by entirely separating the means used for protecting each part, from the means used for protecting any other part of the system, thus making the disconnection of the faulty part contingent only on predetermined conditions within itself.

This method of protection has been utilized to a great extent in England to allow the operation of the transmission system as a true network, which is the only way a transmission system covering a large area can be economically constructed and operated with the minimum liability to interruption. An interconnected system can be operated with a fair degree of freedom from interruption by the use of time-limit relays of various kinds, but this protection at best falls far short of that obtained by the use of the individual differential or balance principle, and is further impaired because, particularly on a large system, the operating combinations are continually changing. As is outlined in this paper, apparatus nowadays does not require the protection, but the integrity of the service demands it.

Contrary to a somewhat widespread impression, the individual differential or balance method of protection does not involve a net increase in cost, considering both investment and operating cost, when applied to a transmission system. An interconnected network allows the greatest utilization of the transmission copper at all times by decreasing power losses and maintaining voltage. Also such consolidation allows the greatest possible utilization of the most efficient generating units connected to the system, and of the diversity factors of the loads in different areas. With an interconnected system, each substation may have several sources of supply, and, in the case particularly of static transformer substations, the operating force may be decreased, or even eliminated, as there will be automatic selective disconnection of any faulty supply circuit without an interruption of service to that substation. These considerations, it is evident, may greatly overbalance the consideration of a possible greater investment in transmission lines and equipment.

The individual differential or balance method of protection may be applied to transmission circuits by:

1. Running external pilot wires for each line or cable. This method is mainly applicable to short underground circuits.

2. Pairing two lines or cables which have the same destination, and operating them regularly as one circuit, disconnecting it only in case of failure of either line or cable. This method is applicable particularly where existing circuits are to be paired.

3. Dividing each conductor into two parts, which normally carry equal currents. This method is applicable to new cables which are usually called "split-conductor" or "divided conductor" cables.

With particular reference to the split-conductor cable, the means of protection consist essentially of a differential current transformer (or its equivalent) for each phase, the current transformer having two opposed primary windings and one secondary winding, connected to a simple instantaneous overload relay, at each end of the circuit. One primary winding is connected in each split to give balance normally. However, end faults and mechanical and electrical limitations in the insulation between splits, complicate the proposition.

In case there is a fault near the far end of a split-conductor cable, the relay at that end will operate due to relative reversal, and disconnect the cable; the relay at the other end evidently will not be affected unless there is sufficient vectorial unbalance between the currents in the two splits. This unbalance cannot be sufficient unless the impedances of the two paths to the fault are considerably different, or the currents are very large, or the splits are separated at the far end with a split switch. With this limiting condition, the end fault, taken care of, faults at other points of the cable present no difficulty.

The introduction of additional reactance results in the best solution, because any acquired unbalance with end faults can be readily obtained at low values of current. The use of a split switch results in high voltages between the splits, even under normal conditions, and full voltage under fault conditions. The insulation between splits must necessarily be relatively small in order to keep down the size and cost of the cable, therefore, these voltages must be avoided so far as possible.

A further protection may be obtained with reactance, that of insuring against the loss of individual differential or balance protection which might result from a fault between splits of one conductor. The chances of such a fault may be remote, but can be simply guarded against without accompanying disadvantage.

This arrangement of the reactance is called an "end" or "selector" reactance, and consists of one small iron core reactance in each split, a total of three reactances being at each end of the cable, which cause the necessary unbalancing between the currents in the two splits with an end fault. From the one-line connection diagram in the figure it will be noted that with an end fault the split currents from the far end are unbalanced because in one current path there is no additional reactance, while in the other there are two additional reactances.

Under normal conditions each split will carry equal currents, and also there will be a voltage between the splits equal to the drop across one of these reactances, which will cause unequal currents to flow in the splits in case of a split fault. Therefore, the cable will be disconnected in case there is a ground, a phase fault or a split fault, and the selective protection cannot be impaired by changed conditions in the cable without disconnection.

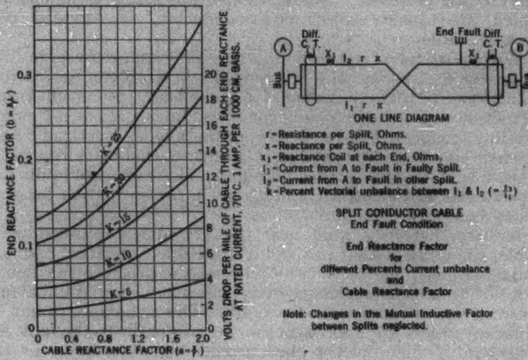

FIG. 1

The curves show the relation between the end or selector reactance and the resistance and reactance of the cable for different percentages of unbalance, *k*, under the end fault or limiting condition. The right hand scale of ordinates shows the end reactance volt drop per mile of cable for the required unbalance at full-load current, on a one ampere per thousand circular mil basis. It is believed that a value of *k* equals 20, is a fair value to use in present practise, which means that the vectorial unbalance of the currents in the splits is 20 per cent of the larger of the two split currents.

The reactance and resistance per split are respectively double their values per conductor. For 350,000-cir. mil sector cable, 13,200-volts, with 6/32×6/32-in. insulation, and 5/64-in. split insulation, the 60-cycle reactance factor is about 0.85. The usual values of reactance factors should range from 0.4 to 0.9 at 60 cycles, the larger cables having the greater factor. For all practical purposes it is evident that 25-cycle cables can be considered to have zero reactance. These curves give a ready means of determining the values of end reactance to use for any desired combination.

The differential current transformers should have a close balance between the primary windings, an allowable unbalance of not more than 0.1 per cent being a desirable amount, also the end reactances should have closely similar saturation curves in order not to disturb the inherent balance between the splits at all current values. The splits are transposed in present American practise near the middle of the cable only, but additional transpositions may be made to keep the balance between the splits within 0.1 per cent. This value is not difficult to obtain with present methods of cable construction.

The importance of close balance is evident when one considers the condition of a through fault with a split-conductor cable feeding short-circuit current to it. The value of this current may be as great as thirty times normal. With an inherent unbalance between the splits of 0.1 per cent and an additive unbalance in the differential current transformers of 0.1 per cent, the total unbalance will become 6 per cent with thirty times normal current flowing. This unbalance naturally must be a safe amount less than that for which the relay will operate, in order to prevent disconnection of the cable.

J. T. Lawson: I would like to call attention to the table headed "Classification Troubles." This heading is incorrect and should read "Classification of Interruptions." The table is not a classification of troubles of the Public Service Electric Company, but a list of the interruptions which we were unable to protect against.

Particular attention should be given to the cable failures. As you will see, the cable failures in 1915 have gone up and these failures include those mentioned by Mr. Pollard; namely, the short circuits between phases.

Short circuits between phases in our system up to this time had been very few in number, most of the failures being single-phase grounds.

The failures mentioned occurred on a certain set of circuits used as tie feeders on which feeder reactances had been installed at each end.

We think the installation of feeder reactances at each end of these circuits may have had the effect of confining any high-voltage condition in these cables, thus causing the failure.

Referring to Mr. Creighton's remarks in regard to interference of telephone systems by power lines, I would point out that the interference to the telephone system by any apparatus which we might install would be a serious problem to a power company. Almost all the large power companies have load dispatchers or system operators who are dependent for their efficient service on the use of the telephone, and any apparatus we might install in our stations which would interfere with the telephone service would seriously interfere with the service which the power company could give by the load dispatcher as he is dependent on the proper working of the telephone wires.

John B. Taylor: Referring first to Mr. Roper's paper, I understand that the system is the four-wire three-phase, 2300/4000-volt with neutral grounded, and this neutral fourth wire is grounded at but one point,—the substation. How is the fourth wire regarded as a lightning risk? Is it provided with arresters?

How are the grounds for lightning arresters made, and is the resistance tested initially or subsequently as a matter of routine?

Regarding the transformer connection boards, which have been removed, it was my impression from reading the paper that the policy of removing them was adopted before the policy of "100 per cent protection." This might mean if the 100 per cent protection had been instituted first, the connection board would not have appeared as the source of so much trouble.

On the paper of Messrs. Pollard and Lawson, I must limit myself to calling attention to what appears a discrepancy between the table "Classification of Troubles," and the statements in paragraphs immediately before and after. The text gives the impression that the various devices have reduced the number of cable troubles, but if I read the table correctly, the figures do not show it. 25-cycle cable failures are listed as 4 per cent in 1913, 5 per cent in 1914, and 26 per cent in 1915, and in the case of the 60-cycle cables the troubles are listed as 14 per cent in 1913, 10 per cent in 1914, and 15 per cent in 1915. Attention may also be directed to the line at the bottom of the table showing yearly "cable failures per mile." It is my impression that the figures do not compare favorably with the cable records on other large systems;—for example, the Commonwealth Edison Company of Chicago, and the Interborough Rapid Transit Company of New York, operating with grounded neutral and comparable voltage. The Institute TRANSACTIONS of several years ago, if my memory serves me correctly, will show failures in the order of one per year for each hundred miles of cable, but representatives of these companies may be able to correct me if in error.* The figures given here are more on the order of one fault for every six or eight miles of cable each year.

This comparison is a pertinent point for consideration. Is this practise of putting a ground solidly on one conductor making trouble, or is there some other explanation of the relatively high number of cable failures?

The troubles on overhead lines have been reduced either by the elimination of poor insulators, the use of arcing ground suppressors, or a combination of the two, but unless I misread the cable figures the record is not good.

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*See A. I. E. E. TRANSACTIONS, Vol. XXVI. Page 1614 for Commonwealth Edison Co. 2 burnouts per 100 mile-years. Page 1641 for Interborough Rapid Transit Co. 0.016 burnouts per mile-year.

J. O. Montignani: The Rochester Railway & Light Company operates outside of its direct-current district a three-phase, four-wire, 4150-volt grounded neutral distributing system, having a total wire length of about 1200 miles, 300 miles of which is underground. We have about 1800 transformers connected to our lines, with a total capacity of 17,000 kilowatts. Previous to the year 1911, we relied for protection against lightning upon multi-gap arresters placed at approximately one-half mile intervals on the more exposed lines. Not only was this quite inadequate protection, but the arresters themselves proved to be a prolific source of trouble and after most lightning storms we usually found it necessary to go out and gather up the charred fragments of a number of arresters. Invariably in burning up, the arresters fused the line wires connected to them, causing very serious interruptions to the service.

During the summer of 1911, when we first began to keep systematic records of our lightning troubles, we lost 99 transformers in thirty-one thunderstorms, being 6.1 per cent of the total transformers then installed. This alarming record decided us to remove all multi-gap arresters from our lines and install outdoor-type electrolytic arresters at exposed parts of the system, and at important junction points on the feeders. This was accomplished in the spring of 1912, and resulted during the summer of that year in reducing our losses to 1.2 per cent with thirty-two thunderstorms. Since that time our annual losses have averaged about 1.5 per cent. That the change was economically justified is shown in the fact that basing our calculations on the reduction of transformer losses from 6.1 per cent to 1.5 per cent, the annual saving in transformers and estimated current sales amounts to a little over $2000, after allowing for interest, depreciation, and maintenance of the arresters. We have not lost a single electrolytic arrester during the four years they have been in operation, and that they are draining our lines of many severe lightning disturbances is well proven by observations we have made.

As compared with the Chicago system, our transformer losses are still very high, but the cost of electrolytic arresters would make prohibitive much further extension of that type of protection. On the other hand, we have got to be satisfied that the installation of a large number of less expensive arresters is not going to introduce greater risk of service interruptions due to their burning up, even though the loss of transformers is reduced thereby. Mr. Roper makes no mention of the number of arresters destroyed annually, and I would like to inquire if he has any record of such loss and consequent interruptions of service. I have spoken with several central station engineers whose experiences have led them to disagree with Mr. Roper's statement that:

"Modern types of arresters comply with the specification that a protective device must be less subject to troubles than the apparatus which it protects."

The results obtained in Chicago by removing the terminal boards from transformers are very interesting and show conclusively that this is a most vulnerable point of the transformer. Our experience in Rochester has been that about 50 per cent of transformers damaged by lightning have had the primary leads burned off due to flashing-over at the terminal board. It would seem, however, that inasmuch as the terminal board serves the useful purpose of supporting and separating the leads as well as facilitating changes in connections, a remedy for its lightning troubles might be found by redesigning terminal boards to provide greater dielectric strength.

R. F. Schuchardt: Too much emphasis cannot be given to the words of caution which have already been spoken with reference to interpreting information based on experience. One must always keep in mind the essential details of the system on which the experience was obtained. For instance, reference is made in this paper to the aluminum cell arrester reducing cable trouble. This reduction is undoubtedly due to the fact that a part of the transmission system consists of overhead sections connecting to underground cables. A few years ago Dr. Creighton made an exhaustive study of the Commonwealth Edison Company's transmission system, which is almost entirely under ground, to see whether there were any surges going on in that system which might be avoided by the use of aluminum cell arresters. The conclusion arrived at at that time was that we were not justified in installing such arresters.

The connections of the Essex power station seem rather unduly complicated. I do not see why the great flexibility of the old series arc system is necessary in a high-tension generating station even when supplying a system as extensive as this.

I want to say a word in reference to Mr. Rider's paper, that consideration must be given to the kind of system to which you want to apply the isolating transformer. Undoubtedly, in many cases, for instance, in a city or village where step-down transformers must be used, it may be advisable to step-down and then to step-up again, thereby getting the isolation and also the additional advantage of regulation on the outgoing line. Or where an existing line, perhaps of inferior construction, is purchased and it is desired to connect it to the system, an isolating transformer may be preferable to wholesale reconstruction of the line: but it cannot be expected to serve as a general panacea for the ills of overhead lines. It may many times be cheaper to weed out the weak spots on lines rather than to put in the rather complicated installation of an isolating transformer with its necessary protective devices.

Peter Junkersfeld: I would like to offer a word of caution against over standardization. I refer particularly to Mr. Roper's paper. That development and investigation in Chicago cost us, not thousands of dollars, but many times tens of thousands of dollars. The conditions there were such that we felt, however, that this particular expenditure of money in that direction would do more in the way of further improving the service than if it were spent in some other direction. The thing which was good engineering in that case maynot be good engineering in some other cases. In fact, similar large refinements in service in other communities in that general section of the country might be undesirable. It is an old saying that you must cut your coat according to your cloth, and the coat must fit the individual. The trimmings on this coat of electric service must fit the community served. In this case it was considered better to put a little more quality in the electric coat than to decrease the price. In many other communities that condition might not prevail, and that point should therefore be emphasized.

David B. Rushmore The report which we have heard gives us the result of a scientific examination of operating conditions. This is a great advance over anything which we have had in the past and offers great promise for future study. In order to make an investigation thoroughly scientific, the factors must be known quantitativelyas well as qualitatively. This means that sometime in the future we must understand the quality and magnitude of the lightning disturbances involved.

With all its disastrous results, it is interesting to know that lightning is of some benefit. It is estimated that at least one hundred million tons a year of nitric acid are formed by the lightning discharges, and this is carried to the earth by the accompanying rain. On this source we are very largely dependent for the supply of nitric acid which is such an important part of the food of vegetable life and, indirectly, of animals.

D. W. Roper: We do not use the neutral wire for overhead lightning protection. Our neutral is grounded at each substation. At each transformer where an arrester is installed on the outer wire, an arrester is also installed on the neutral wire. A ground rod is used for the ground connection. In Chicago, there is no difficulty in securing good grounds as the water level is only a few feet below the ground level.

The load in Chicago on the underground cables does not operate quite as well as the figures given by Mr. Taylor would seem to indicate, but excluding burnouts due to external causes, such as a pick being driven into a cable or some other similar disturbance, the faults in the 9000-volt cable average from two to four per hundred miles per year.

N. S. Diamant: I would just like to touch on the question of sudden short circuits. The authors speak of "the maximum short-circuit current" that will flow into a fault, and they give the curves of Fig. 4 to further illustrate this point. Now, I take that by "maximum short-circuit current", in per cent of the full-load current, the authors wish to refer to the most unfavorable condition possible which will take place if the sudden short circuit were to occur near the zero point of the e.m.f. wave. In this case the current will overshoot and reach nearly twice the value it would have if the short circuit were to occur very nearly at the maximum point of the e.m.f. wave. It seems to me—although it is not clearly stated by the authors—that in Fig. 4 they have given us the most favorable condition of a short circuit under the assumption of ideal machines (of 15 per cent reactance each) with no damping effect. This damping may be roughly taken into consideration, if desired, but in any case I think that it is best to refer the curves and the discussion of a short circuit to the worst possible condition. This point should have been made clear by the authors: thus according to my interpretation of the connection of the six alternators under consideration, the rush of current with 5 per cent tie-bus reactance per generator will be anything between 30 and 60 times full-load current—rather than 30—under the ideal condition of no damping. Similarly for the other points of the curves.

H. Mouradian (communicated after adjournment): Mr. Roper's contribution appears to be the first published report of a systematic attempt to study the lightning problem experimentally in the field (rather than in the laboratory), where, it seems to the writer, the problem must receive its ultimate solution.

A study in the field, along somewhat similar lines, has been conducted by The Bell Telephone Company of Pennsylvania during the period 1911 to 1916, this study comprising the observation of lightning effects as influenced by various degrees of protection upon the telephone cable plant in the entire state of Pennsylvania, the entire state of Delaware, part of the state of New Jersey, and certain sections of the states of West Virginia and Ohio. This study included the observation of lightning effects as associated with approximately 25,000 cable pairs, fully protected by means of open space cutouts, and, roughly, 500,000 telephone stations.

As Mr. Roper's paper relates to transformer protection, and the data collected by The Bell Telephone Company of Pennsylvania relate to cable protection, this discussion will only consider some of the broad points involved in the field observation of lightning effects.

As noted by Mr. Roper, "the variations of the lightning itself overshadow the rest of the variables." This is borne out by our experience. In the western half of the state of Pennsylvania, the number of substation arrester operations varied from a maximum of 11,594 operations in 1912 to a minimum of 2962 operations in 1915, a variation in lightning activity of approximately 400 per cent, no change whatever having been made in the type of substation arresters in the meantime.

In reference to the extreme irregularity in the distribution of lightning effects, it appears to us, in view of this feature, that only through observations covering a large area carried out over a considerable number of years, will it be possible to secure reliable data. Our experience to date has been such that the writer can unqualifiedly endorse Mr. Roper's conclusion 12, to the effect—"Great care should be used in attempting to draw general conclusions from the experience obtained from a fewarresters or during a single season, or from a limited area." It seems best to make no changes in the protection practises in a given area, and to carry out the work of observation for possibly five or six years before drawing final conclusions.

In reference to the two other methods of observation indicated in Mr. Roper's paper, first, the study of the trouble caused by lightning in relation to the number of lightning storms, and, second, the study of the relation of fuse troubles to transformer burnouts,—we have found the first mentioned method very unpromising in our work. As regards the second method, our experience with fuse operations, as compared with other lightning troubles, is that the fuse operations appear to bear a closer relation to the intensity of lightning storms than other types of troubles caused by lightning, such as breakdowns in insulation, particularly in telephone work where practically no power current will follow the path of the lightning current.

The writer would like to suggest that Mr. Roper is probably incorrect in his deduction in section IX of his paper, "Increasing the Size of Transformer Primary Fuses," that increasing the size of fuses from five amperes to twenty-five amperes would not materially change the number of fuse operations.

One other point of similarity, which may or may not be accidental, is in reference to the reduction in fuse operations in 1915 as compared with the fuse operations in 1913, shown on Fig. 13 of Mr. Roper's paper. In the state of Pennsylvania, the number of telephone substation fuse operations decreased from 11,546 in 1913 to 4,975 in 1915, the fuse operations being intermediate (6,913) in 1914. There has been no change in our substation protection practises in the same interval of time. It is very possible, therefore that a large part of the reduction in fuses blown (to explain which reduction certain hypotheses have been made by Mr. Roper) may have been simply due to the difference in the character of the 1913 and 1915 lightning seasons. It may be of interest here to note that the telephone substation fuses in use, associated in series with the substations open-space cutouts, wired in ahead of these cutouts, viz., towards the line side, are rated as 10-ampere capacity. As pointed out by Mr. Roper the difficulty of reaching accurate conclusions is very great, and the observer has to be continuously on guard not to ascribe to improved practise what may be simply due to absence or difference in character of lightning.

The writer would also like to suggest that Mr. Roper's last conclusion may be considerably in error, and that if Mr. Roper should continue his interesting experimental work, without further changes in the protection conditions of the 4,000-volt transformers, the future may show a very material increase in the ratio of the percentage of transformer burnouts in the class A areas to the percentage of transformer burnouts in the class C areas.

One detail point seems worth referring to. It appears to the writer that the data presented in Mr. Roper's paper indicate, if the difference in the character of the lightning seasons is not taken into account, that the increase in the ratio of arresters to transformers should be credited with a larger percentage of responsibility than the 20 per cent indicated in Mr. Roper's summary, probably as high as 50 per cent. This thought is suggested by the study of Table VIII and Mr. Roper's own statement, in regard to this same table, that "the percentage of fuses blown in class A is less than one-third of that in class C."

Another thing the study of Mr. Roper's paper suggests, and about which the writer would like to secure Mr. Roper's opinion is whether, considering the question purely from the standpoint of lightning protection, the troubles from blown fuses would not be materially reduced, if the grounds at the substations on the neutral wires were removed.

N. L. Pollard: Replying to Mr. Taylor's question concerning the increase of cable troubles as indicated by the table, will say that the total number of troubles per mile of cable and overhead lines has decreased for the 60-cycle system but has increased slightly for the 25-cycle system. The slight increase on the 25-cycle system is undoubtedly due to the fact that we have not installed on this system the protective apparatus to the extent that we have on the 60-cycle system.

The failures on the 60-cycle cables alone, increased materially in 1915. This, we think, may be due partly to the installation of feeder reactances on both ends of the tie feeders connecting our City Dock, Marion and Essex Stations. Since the installation of these reactances, the nature of the cable breakdowns has changed from a single-phase failure to ground, to a breakdown between phases. The majority of the cable breakdowns has occurred on the tie feeders equipped with these reactances and we are led to believe that the installation of the reactances must have some bearing on the breakdowns.

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MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS

BY F. L. HUNT

Abstract of Paper

This paper gives the results of megger tests made on disk insulators on a 66,000-volt transmission line in central Massachusetts after 2.5 years' operation. In one lot of 4410 insulators tested 9.77 per cent tested less than 2000 megohms. The percentage of failures in different positions in the string is given on both strain and suspension towers. The actual cost of making these tests under different conditions of weather and of service requirements is given per insulator on the line, per bad insulator and per tower. The cost per insulator on the line, of testing only, varied from 7.3 cents to 11 cents. The cost of replacing bad insulators was 74.5 cents per bad insulator, not including the cost of the replacing insulator.

Laboratory tests made on 30 of the bad insulators taken from the line showed that those which measured very low by the megger fail on 60-cycle tests much below spark-over value, while those with medium high resistance may reach flash-over value and then puncture within one minute. Some insulators which show infinite resistance by the megger, and which withstand arc-over potential at 60 cycles, will fail under high-frequency test immediately.

DURING the latter part of 1915, megger tests were made on all the insulators on one circuit, and part of the insulators on the other circuit, on nineteen miles of 66,000-volt, double circuit transmission line in central Massachusetts. These circuits are supported on galvanized steel towers, three wires to each circuit spaced 10 ft. (3m.) apart vertically, the two circuits spaced 18 ft. (5.4 m.) apart horizontally, the bottom wire 45 ft. (13.7 m.) from the ground, average span, 550 ft. (167.6 m.)

The total number of insulators tested on this line was 4410. These were suspension type insulators hung with four per wire on suspension towers and five per wire on dead end towers. Numbering the insulators from 1 to 5, beginning at the cross arm, the number of failures in each position is shown in the following tabulation.

Strain towers.

Unit number	1	2	3	4	5
Total number	486	486	486	486	486
Total damaged	50	43	47	51	64
Per cent damaged	10.28	8.84	9.67	10.49	13.16

Standard suspension towers.

Unit number	1	2	3	4	
Total number	495	495	495	495	......
Total damaged	61	32	47	36	......
Per cent damaged	12.32	6.46	9.49	7.27	......

The above results seem to indicate that there was no logical relation between the number of failures of the insulators in any given position and their distance from the conductors.

Cost of Tests

It was necessary in testing these insulators to take one circuit at a time, so that all the towers had to be gone over twice. Of the total number of 4410 insulators tested, there were 2430 dead end insulators, of which 255, or 10.5 per cent, were bad; and 1980 suspension insulators, of which 176, or 8.9 per cent were bad, as indicated by megger tests above.

A crew of three men was used in making the tests and twenty week days and twelve Sundays were consumed.

The total cost of the tests, including cost of transportation, was $424.69.

The insulators on one circuit were tested on 180 towers and on the other circuit on 69 towers. The cost per tower per circuit on the first 180 towers was $1.97. The cost per tower per circuit on the 69 towers was $1.02 each. The average cost of the whole job was therefore $1.70 per tower per circuit, and 9.6 cents per insulator tested, where only one circuit could be tested at a time with the other circuit alive during the testing.

The variation in cost per tower in the two parts of the job was due almost entirely to the difference in weather conditions. In the first case the weather was cold and the insulators were covered with frost, so that the work could not be started until about ten o'clock in the morning. The men were also stopped several times by rain, so that considerable time was lost, and this section of the testing included most of the Sunday work.

The total cost of replacing the 431 bad insulators was $322.27 or 7. 3 cents per insulator on the line and 74.5 cents per bad insulator. The total labor cost of testing and replacing bad insulators on the line was therefore 16.9 cents per insulator of the total number or $1.73 per bad insulator. This does not cover the cost of new insulators. If it had been necessary to pay for new insulators, the total cost per bad insulator would have been three times the original cost.

These insulators were in use less than three years, having been installed in the early part of 1913, put into operation in May, 1913, and tested in the latter part of 1915.

A recent inquiry made from an insulator manufacturing company brought out the fact that they would add 4 cents per disk to the price of the insulators in order to cover the cost to them of putting their insulators through a high-frequency test before shipment. If such a test would have taken out the insulators that have failed during the first 2.5 years of operation, it would appear that 4 cents additional in the initial price would have been a good investment, since the cost of testing and replacing bad insulators has amounted to 16.9 cents per disk on the line.

Another section of line of about the same length upon which insulators of a different design had been installed, was tested at a cost of 7.3 cents per insulator, which is slightly less than the cost per insulator in the first case. Due to the fact that both circuits were tested at the same time, each tower had to be climbed but once. The insulators in this second case showed less than one per cent of failures and, on this account, it was not considered necessary to replace the bad insulators, since there was no case in which more than one bad insulator occurred in one string.

LABORATORY TESTS

To get definite information regarding the nature of the faults in the insulators they were shipped to a laboratory where the following tests were made with the co-operation of Mr. E. E. F. Creighton and Mr. P. E. Hosegood.

The total number of insulators selected was 40. Thirty-five of these were taken from the line and five were new insulators. Twenty-one measured below 10 megohms, eight measured 22 to 52 megohms, one measured 220 megohms, five from the line measured infinity, and the five new insulators measured infinity, making up the total of 40.

Test 1. Eleven of the insulators which meggered below 10 megohms had 60-cycle voltage gradually applied to them until they punctured. Not one of them reached flash-over value.

The voltage was very gradually raised and the lowest puncture voltage was 22 kv., the highest was 52 kv., and the average of the 11 was 39 kv.

Test 2. Seven of the insulators which measured between 22 and 52 megohms and the one measuring 220 megohms had arc-over voltage applied to them until they punctured. Four of them punctured immediately, 2 of them punctured in one second, one in four seconds, and one in thirty seconds. There is no relation between the megger readings and the time of puncture.

Test 3. In this test a constant voltage far below the arc-over value was applied until puncture occurred. Seven insulators measuring below 10 megohms were tested. The first five had applied to them 20 kv. They punctured in from one to thirty seconds. Two more were tested at 15 kv., one puncturing in one second, the other in six seconds. There is no consistency between the puncture voltage and the megger readings as sufficiently illustrated by the last test. In this test one of the insulators measured three megohms and the other below one megohm, but the higher resistance insulator took one second to puncture whereas the other insulator with lower resistance took six seconds to puncture.

Test 4. Spark-over voltage of 60 cycles was applied to the 10 insulators which measured infinity. Three of these punctured in less than 45 seconds. This is 30 per cent loss on 60 cycles.

Test 5. The remaining seven insulators which had shown O.K. on a minute's test on 60 cycles at flash-over voltage, were next tested on the oscillator using a frequency of approximately 200,000 cycles per second. Flash-over voltage only was applied. Two of the seven punctured in less than one minute. This is again about 30 per cent of the insulators that were left. The remaining five withstood super-spark potential of 120 kv. for 10 seconds each.

Conclusions. The results of these tests are similar to others that have been made and show, first, that insulators which measure very low will fail almost immediately on a 60-cycle test voltage, much less than spark-over value. Insulators with medium high resistance may reach flash-over value of potential and will puncture within a minute. Insulators of infinite megger reading may have faults developed by the arc-over potential within one minute's application. After the faulty insulators have been eliminated by the 60-cycle test, still further faults are found by the oscillator.

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EXPERIENCES IN TESTING PORCELAIN

BY E. E. F. CREIGHTON

ABSTRACT OF PAPER

The paper gives the results of numerous experiences in testing porcelain insulators particularly in regard to porosity, absorption of water, surface leakage and dielectric losses. Considerable energy is required to drive moisture out of a porous insulator and it has been found best to restrict the oscillator testing to dry porcelain, whereas the wetter the porcelain the more effective is the 60-cycle test.

THE FOLLOWING experiences in testing porcelain insulators and the resultant deductions are given as an addition to the development of the relating science and practise.

For the present purposes the resistances of insulators may be classified as follows.

1. Distributed resistance due to water in pores.
2. Concentrated resistance due to water in cracks.
3. Surface leakage (external).
4. Dielectric losses (equivalent resistance).

I—DISTRIBUTED INTERNAL RESISTANCE

Wet-process porcelains have been examined having a porosity much less than 0.01 of one per cent by weight. Dry-process porcelains have a usual porosity of 1 per cent to 2 per cent. The pores are fissures, visible to the naked eye if a stain is used to color them. These porcelains take up water rapidly simply by soaking an hour. As the porosity decreases the water meets more and more opposition to its entrance by the back pressure of the air entrapped in the pores. Under conditions easily reproducible in the laboratory a porous body covered with a liquid will remain perfectly quiescent for a minute or two while the liquid is soaking in from every side. Finally the internal air pressure becomes great enough to break through the wall of water and a stream of bubbles will break forth. Where the porosity is very small the porcelain, soaked for months in a bath of water, refuses to take up the water. Still this same insulator on a transmission circuit will take up sufficient water to reduce its internal leakage resistance to as low as 300 megohms. This difference in absorption is due to the changes in temperature. An increase in temperature causes an expansion of air which drives some of it out. Subsequently it breathes in moist air and moisture. Each temperature change causes a deeper penetration until, by fractional distillation, there is a conducting path between surfaces. The necessary period in such a case may extend over several months.

Such slightly porous and wet insulators still retain some value as insulators but they are a menace since they will fail rapidly under an increase in potential. Such an increase may take place suddenly by the failure of another unit in series with it.

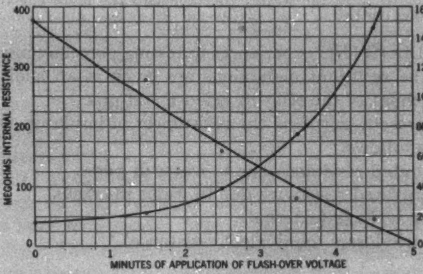

FIG. 1

A rare case of porosity was studied. Fig. 1 shows the relation of internal resistance and wattage loss, both relative to the time. On the application of 60-cycle potential, at flash-over value, the resistance gradually decreased from 380 megohms to zero in five minutes. The wattage rose from 16 watts, slowly at first, then with a rapid increase as the water and porcelain were heated up by the ohmic loss ($E^2 \div R$). At the end of 4.5 minutes the loss was 145 watts. At the end of 4.5 minutes the total energy given to the insulator was 14,000 joules. An unknown portion of this energy was radiated and conducted away during the four periods of interruption of potential test, to measure the ohmic resistance. Calculating the maximum possible temperature, from the energy loss and the specific heat, it must have been less than 80 deg. cent. at the instant of puncture of the porcelain. The estimated energy was 20,000 joules including the heat conducted and radiated away. A continuous application of potential would have shortened the period before puncture occurred. It is seldom that a porous insulator withstands application of flash-over potential for even one minute.

With even distribution of moisture throughout the head of the insulator and taking 140 cu. cm. as the volume under stress, the average energy per cubic centimeter to cause puncture was approximately 143 joules.

In testing such porcelain for porosity the methods which have been previously recommended are inadequate. The following precautions are taken to get greater accuracy.

1. Evacuation of the porcelain at a micron of pressure or less is carried on for about eight hours.
2. The air is removed from pure water by boiling and evacuation.
3. Water is poured over the porcelain samples without breaking the seal.
4. Subsequently the seal is broken and the samples are allowed to soak a week in water.
5. The surface of the samples is carefully and quickly dried and the weight taken. The error of weighing is not greater than 1 in 100,000.

On samples of low porosity this method may put five-fold more moisture in the pores than the method previously recommended.

II—CONCENTRATED RESISTANCE

Concentrated moisture in cracks or spots causes a rapid rise in temperature and consequently there lapses a brief period before puncture. A crack a mil wide (0.0025 cm.) 2 cm. long and 2 cm. deep would have a volume of 0.01 cu. cm. and the time to cause puncture at flash-over voltages might be no greater than 0.01 second, assuming the specific resistance of the water to be one million ohms. At any rate the period would be brief.

As a rough method of analysis it may be assumed in general that insulators are porous which on measuring less than 600 megohms, withstand for many seconds a potential nearly equal to flash-over value. On the contrary, insulators which puncture quickly are either cracked or possibly porous in a local spot.

III—SURFACE LEAKAGE

The resistance to surface leakage will depend, evidently, on the thickness and nature of the deposited material on the surface of the insulator. Using a thin layer of washed clay and varying the humidity, the curves of resistance versus humidity are given in Fig. 2.

The following is a record of one insulator of several which were coated with dust (porcelain slip) and placed in a wooden box where the humidity was gradually increased to a high value and then decreased. The total period of test was 20 days. Surface resistance tests were made from time to time. Fig. 2 shows the relation of surface resistance to humidity in the box. Naturally there was a little lower resistance on increasing the humidity than on decreasing it due to the fact that the humidity was introduced by heating water in a receptacle placed underneath the box and connected to it by means of a tube. The variation in resistance on the up-curve and down-curve, however, is not very great except at extremely high humidities where there is comparatively little interest. This curve may be considered the extreme condition in dusty countries where there is a long dry season so far as rain is concerned but where fogs and dews take place. If an insulator is in service, the leakages of current over the surface would give sufficient heating effect to prevent the lowering of the resistance to the very low value obtained in these tests. These conditions might exist, however, where the line is out of service for testing purposes.

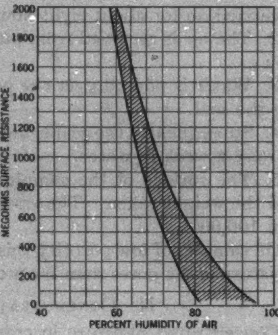

FIG. 2

Naturally the condensation of moisture on a surface of this kind depends on differences of temperature between the insulator surface and the surrounding atmosphere and also upon the humidity of the atmosphere. No attempt is made in the tests to take this factor into account but it is of course the condition which appears so prominently at sunrise.

Increasing the size of an insulator does not necessarily increase its resistance. On the contrary, the larger insulators, due to their shapes, usually have a less surface resistance than the smaller insulators, other things being equal. The tests correspond with the theoretical calculations.

A little salt or carbon added to the film of dust, lowers the surface resistance below the values given in Fig. 2 at the same degree of humidity.

The following tests were made to determine how long it takes a dusty insulator to dry off. A large pin-type telephone insulator was coated with porcelain slip, containing no free acid or alkali. The resistance of the surface coating of clay was initially 88,000 ohms. The insulator was allowed to stand in an atmosphere which had a humidity of 36 per cent and a temperature of 23 deg. cent. The porcelain slip was at the same temperature as the room. After half an hour the moisture had sufficiently dried off the surface of the insulator to give 300 megohms resistance. At the end of another half-hour, making a total of one hour, the resistance had risen to 2000 megohms.

IV—Dielectric Losses

The losses in solid porcelain, for intermittent wave trains, are negligible. The dielectric hysteresis of air is too small to measure. However, if the entrapped air in porcelain is strained beyond its electric strength it forms hot corona, which not only destroys its own dielectric strength but also damages the cell walls of porcelain which enclose it.

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The Practise of Testing with the Oscillator

Factory practise calls for oscillator tests on the porcelain parts as they come from the furnace. The parts should not be partially immersed in water for the tests as is usually done in testing at 60 cycles. Caps and pins may be loosely applied to the porcelain, and the corona at high frequency will satisfactorily fill the intervening air spaces. The high frequency and the higher test voltage obtained in the oscillator method of testing finds, on an average, 8 per cent more faulty porcelain than the 60-cycle method. Occasionally where porcelain is only slightly porous and dry, it easily withstands the 60-cycle test and the oscillator has removed as much as 25 per cent of the number that have passed the 60-cycle test. The 60-cycle method becomes more effective if the porcelain is porous and wet. For this reason in testing line insulators the oscillator as recommended in a previous paper must be somewhat modified. It is necessary to make the tests, first with 60 cycles to eliminate the wet porous insulators; then with high frequency to find the dry porous and otherwise weak ones. In applying the 60-cycle test, time is saved by applying the voltage to all the disks of two strings simultaneously.

It has been shown that the energy necessary to drive out the moisture in a porous insulator is considerable. The oscillator has extremely high power but the wave trains die out quickly. It is, therefore, necessary to restrict the oscillator to the testing of dry porcelain. The wetter the porcelain the more effective the 60-cycle test and the drier the porcelain the less effective the 60-cycle test and the more effective the oscillator test in detecting porous porcelain. Even if there were 100 oscillations in each wave train the potential would be applied only about 1/20 of the time. In other words, the I^2R loss in the leakage of the insulator would be less than 1/20 of what it would be at 60-cycles at the same voltage. Consequently it will take a much longer time to heat up the water in the pores of the porcelain than with an equal 60-cycle voltage.

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A NEW METHOD OF GRADING SUSPENSION INSULATORS

BY R. H. MARVIN

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Abstract of Paper

Attention is drawn to the known disadvantages of the uneven distribution of voltage in long strings of disks. The general theory showing how the distribution is determined by the various capacities of the units is given. It is shown how the distribution can be improved by grading, or varying the internal capacity of the units.

The proposed method of grading consists in placing flat metal rings on the insulator, around the cap and stud respectively, the porcelain disk being enlarged for this purpose.

A simple method of measuring the voltage distribution is described using a single needle gap.

The results of tests with and without grading are given, the graded strings showing a decidedly better distribution of voltage.

Introduction

THE UNEVEN distribution of voltage along a string of suspension insulators is well known. With a small number of units this feature is not serious, and scarcely justifies the complication and expense required to overcome it. But with an increasing number of units, the distribution becomes continually poorer. A limit is soon reached where additional units make no appreciable increase in the potential of flash-over. It is believed that any further increase in operating voltages will necessitate a consideration of this problem.

In general, the unit next to the line has the largest proportion of the voltage across it, the succeeding units taking a smaller and smaller amount. This is unsatisfactory for two reasons; the units near the line have to stand an excessive strain, the units near the tower or grounded end have a lower voltage across them than is desirable for efficient service.

A number of plans for improving the voltage distribution have been suggested. These all consist in varying the electrical characteristics of the successive units in a definite manner, and a string of insulators so arranged is said to be graded. The object of this paper is to describe a new method of grading, and to show some results obtained with it

Before proceeding it is advisable to give a brief discussion of the fundamental principles involved in grading a suspension insulator.

THEORY OF GRADING

The distribution of the impressed voltage along a string of units is determined by the relations among the four groups of capacities involved. (1) The capacity through the porcelain between the cap and stud of each unit, which may be called the internal capacity. (2) The capacities between the metal fittings and the earth or grounded objects. (3) The capacity from a metal fitting on one portion of the string to any other portion of the string. (4) The capacity between the metal fittings and the line wire. In theoretical discussions only the first two groups are usually considered, but experiments indicate that the others have an appreciable effect.

Considering the first three groups only, the capacitances in a string of units may be represented as in Fig. 1. For the sake of clearness, only part of the capacities between the various parts of the string are shown.

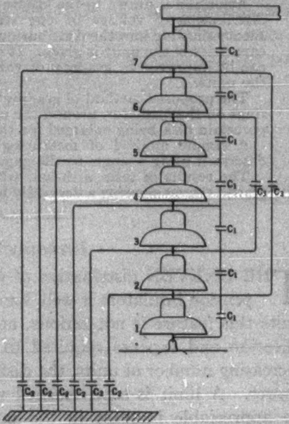

FIG. 1

It is readily seen that the current to charge all the capacities C_1, C_2 and C_3 must pass through the internal capacity C_1 of unit No. 1. The internal capacity C_1 of unit No. 2, has to supply current to the succeeding C_1 capacities, but has a smaller number of C_2 and C_3 capacities to charge. Consequently the first unit has a higher voltage across it than the second. The same reasoning applies to the other units. It appears, therefore, if we neglect the C_3 capacities, that No. 7, the grounded unit, will have the lowest voltage across it. The capacities C_3 tend, however, to make the voltage across the middle unit the lowest, so that the total result is that one of of the units near the grounded end, and not the grounded unit, has the lowest voltage across it. This will be seen in the experimental curves to be described later.

The principle of grading consists in varying the internal capacity C_1 from unit to unit, so that the voltage across each unit is kept as nearly as possible the same. This means that the unit next to the line must have the greatest internal capacity, C_1, and successive units, decreasing amounts.

METHOD OF GRADING ADOPTED

To obtain the necessary variation in the capacity from cap to stud, the following plan was devised. Sheet metal rings are placed around the cap and stud where it is desired to increase the internal capacity. By varying the width of these rings, the capacity can be varied over a considerable range. Of course the external capacities C_2 and C_3 of the unit are also varied by this, but not in the same proportion as C_1. To secure a perfectly even distribution of voltage, it would be necessary to have each unit different, entailing great complication, and rendering manufacture very difficult. It was therefore decided to make a compromise, and divide the string into two, three or more groups, each group having different characteristics from the others.

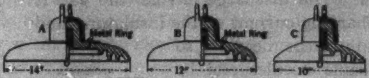

FIG. 2

Fig. 2 shows three different sizes of units designed for use in a three group string. On account of the width of the metal rings, it is necessary to increase the diameter of the porcelain so as to give the correct flash-over voltage. The metal rings are stamped or spun out of sheet metal. They are held in place by the cap, and by the cement around the stud. A string would be composed of a certain number of *A* units next to the line, followed by a number of *B* units, while the rest of the string to the tower end would consist of the plain *C* units.

MEASUREMENT OF THE DISTRIBUTION OF VOLTAGE

Before proceeding with the results obtained, it is advisable to give a brief description of the method of investigation.

It is evident that a flash-over test is useless as an indication of the strains at normal voltage, due to the equalizing effect of the corona preceding the spark. Some method must be used in which only the normal voltage is applied. Several very ingenious forms of potentiometers have been devised by Prof. Ryan for this purpose. Conditions, however, did not permit of using one of these, and the following method was therefore devised. While it cannot be considered an exact method due to several inherent sources of error, it is thought to be sufficiently accurate to give a satisfactory idea of the distribution. It has the advantage of being very simple, and requiring very little apparatus.

A small needle gap is provided having the minimum amount of metal in the parts in order to keep the capacity as low as possible, Fig. 3. In our experiments the gap was about ¼ in. (6.3 mm.). This gap is placed across each unit in succession and the total voltage across the string which causes the gap to go over is noted. The gap setting is kept the same throughout the test. See Fig. 4. The discharge across the gap is only the charging current of the insulators, and does not injure the needles, so that the same needles can be used throughout. In general, we wish to know what percentage of the total voltage is impressed on each insulator, and the percentage of the voltage across each unit in terms of that across some particular unit. It was found most convenient to base results on the line unit, as in all our work it showed the greatest voltage.

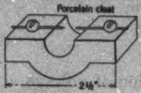

FIG. 3

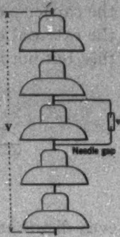

FIG. 4

The units will be numbered from the line towards the grounded end. The line unit being No. 1; the ground unit No. n, or the total number of units. Let v' = spark voltage of needle gap.

$V_1, V_2, V_3, \ldots, V_n$ = total voltage across the string when gap discharges across Nos. 1, 2, 3, etc., respectively.

$v_1, v_2, v_3, \ldots, v_n$ = voltage across units Nos. 1, 2, 3, etc., when total voltage is V_1.

$p_1, p_2, p_3, \ldots, p_n$ = voltage across each unit as a per cent of that across the line unit, No. 1.

$P_1, P_2, P_3, \ldots, P_n$ = per cent of total voltage across each unit.

S = sum of $p_1, p_2, p_3, \ldots, p_n$.

Then the calculations can be arranged as in Table 1.

TABLE I.

Unit No.	v	p	P
1	$v_1 = v'$	$p_1 = 100$	$P_1 = 100\ p_1/S$
2	$v_2 = v'V_1/V_2$	$p_2 = 100\ v_2/v_1 = 100\ V_1/V_2$	$P_2 = 100\ p_2/S$
3	$v_3 = v'V_1/V_3$	$p_3 = 100\ v_3/v_1 = 100\ V_1/V_3$	$P_3 = 100\ p_3/S$
4	$v_4 = v\ V_1/V_4$	$p_4 = 100\ v_4/v_1 = 100\ V_1/V_4$	$P_4 = 100\ p_4/S$
n	$v_n = v\ V_1/V_n$	$p_n = 100\ v_n/v_1 = 100\ V_1/V_n$	$P_n = 100\ p_n/S$

It will be noticed that if only percentages are required, it is unnecessary to know v', the gap voltage, and the second column may be omitted.

The errors in the method are due to the capacity of the gap and its leads, and the possible effect of surrounding objects on the spark voltage of the gap.

Results of Tests

Experiments were made on strings of 15 units. The method used was to obtain the distribution on the ungraded units, and then observe the change due to grading in various ways. For experimental purposes the effect of the metal rings was readily obtained by painting the porcelain with a conducting varnish. The string was placed outdoors to avoid the effect of the walls of the building. An iron pipe placed horizontally was used to represent the cross-arm, and the string of insulators was suspended vertically from this, the lower end being about 10 ft. (3 m.) from the ground. A clamp was attached to the string, and held a metal pipe to represent the line wire. The frequency used was 60 cycles.

Fig. 5 gives the results of tests on an ungraded string. Curve No. 1 shows the values of p, the percentage that the voltage on each unit is to that on the line unit. If the distribution of voltage were uniform a horizontal line at 100 per cent would be obtained instead of the drooping curve, No. 1. It will be seen that the lower portion of the curve is nearly horizontal and that the fourth unit from the grounded end has the lowest voltage across it. Curve No. 2 gives the distribution of voltage along the string in per cent of the total voltage. Each successive ordinate is obtained by adding the value of P for that unit to the preceding ordinate. A uniform distribution would give the dotted straight line, No. 3.

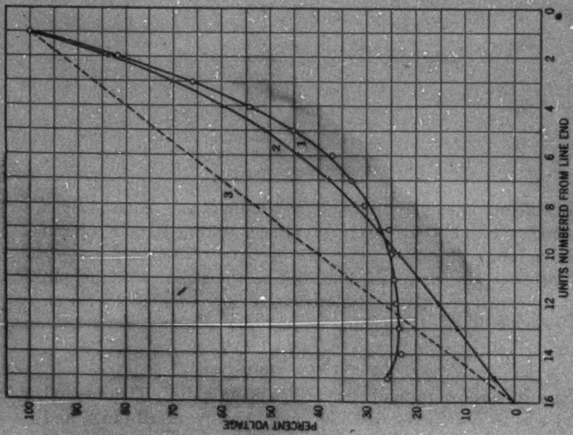

FIG. 6

1—Voltage across each unit in per cent of that across one nearest line
2—Distribution of voltage to ground along string
3—Ideal distribution of voltage to ground along string

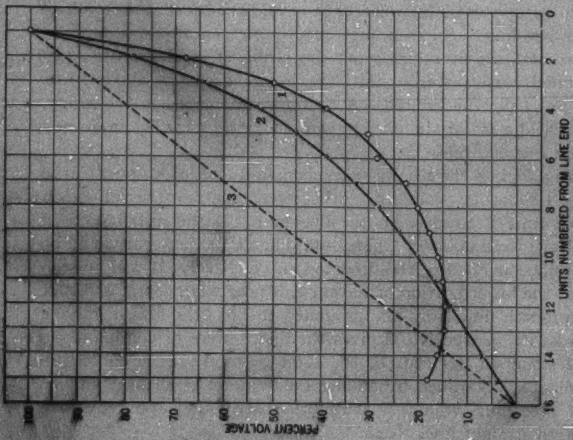

FIG. 5

1—Voltage across each unit in per cent of that across one nearest line
2—Distribution of voltage to ground along string
3—Ideal distribution of voltage to ground along string

Fig. 6 shows similar curves for another type of ungraded unit. In this the internal capacity has a higher ratio to the external capacities. On this account the distribution of voltage is appreciably better, although far from ideal.

Fig. 7 gives the result of grading the type of unit used in the tests of Fig. 6. In this case the three units next to the line had the largest conducting disks, and a high internal capacity. The next five units had a somewhat smaller capacity. The last seven units had no coatings. Instead of uniform curves, the result is a broken line formed by joining the curves due to each group. Comparing this with Fig. 6, a great improvement is

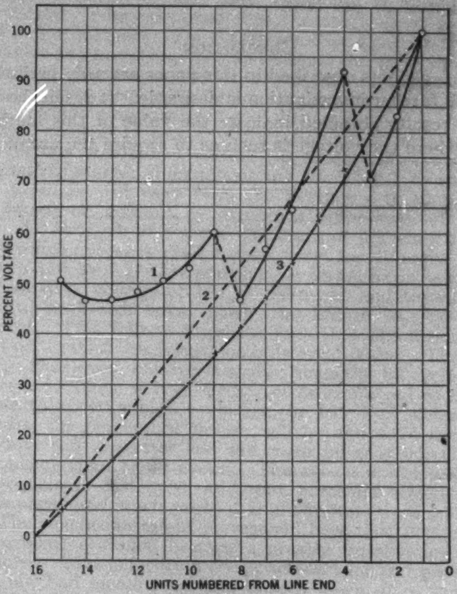

FIG. 7

1—Voltage across each unit in per cent of that across one nearest line
2—Ideal distribution of voltage to ground along string
3—Distribution of voltage to ground along string

evident. Curve 1 is greatly raised toward the horizontal, and curve 3 is nearer curve 2, which represents perfection.

The efficiency of the lowest unit compared to the line unit has been brought from 23.5 per cent up to 46.5 per cent, or nearly doubled. This results in reducing the proportion of the total voltage on the line unit from 16.5 per cent to 11 per cent, a reduction of 27 per cent.

CONCLUSION

The experiments described in this paper are only preliminary and much further investigation is desirable. It is felt, however, that the results obtained indicate the value of this method of grading where the voltage is such as to require the use of many units.

DISCUSSION ON "MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS" (HUNT), "EXPERIENCES IN TESTING PORCELAIN INSULATORS" (CREIGHTON), "A NEW METHOD OF GRADING SUSPENSION INSULATORS" (MARVIN), CLEVELAND, OHIO, JUNE 28, 1916.

F. W. Peek, Jr.: I would like to say a word of warning on the danger of misinterpreting data, especially in regard to insulator testing. I have noticed that there is a great tendency to do this. For instance: The conclusion that a certain specified test is better than another test, and selects the good insulators from the bad, because a greater percentage of insulators are destroyed by that test, may be erroneous. It is, perhaps, best to take a practical example by way of illustration.

It is bad practise to test any insulation up to within a few per cent of the breakdown voltage, as damage always results. The strength of a given thickness of any given kind of insulation *in good condition* will vary from the average 5 to 10 per cent plus or minus on account of structural differences, etc. For instance, the strength of a given thickness of porcelain *in good condition* which averages 100 kv. may vary, for different pieces, from 90 to 110 kv. If this porcelain is arranged in insulators with a flash-over voltage of 100 kv. 60-cycle, and tested at 60 cycles until flash-over takes place, the failure will be about 50 per cent. This follows from the fact that the strength of about 50 per cent of this insulation is below 100 kv. The high-frequency flash-over voltage is higher than the 60-cycle flash-over voltage.* Thus, if high frequency is employed so that it is possible to apply a higher voltage, or 105 kv., before arc-over occurs, the percentage failure will be about 75 per cent. In the above test a greater loss will occur on *good* porcelain at high frequency than at 60 cycles. The action is not selective, much porcelain is destroyed, and that porcelain which passes will be damaged and much worse than if the tests were not made at all. The conclusion might be reached here that better insulators are being obtained because a greater number are being broken down. This is far from the actual fact for this particular case. A few bad pieces are being broken down, it is true, but much of the good porcelain is also being destroyed, and all of it is being damaged. This is an extreme case and the peculiar conditions obtain because the puncture voltage is so near the arc-over voltage, and an arc-over voltage test is specified. It is a bad test for this particular design.

Naturally, this does not mean that this insulation should not be tested. It means that it should be tested at a voltage lower than the minimum voltage at which good porcelain of this particular thickness and shape will be damaged or broken down. Fortunately, the condition which exists for the above insulator does not obtain in most insulator tests, as the designs are usually such that the puncture voltages are much higher than the flash-over voltages. This should, in general, be the case, when the high-frequency test becomes useful.

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* "High-Frequency" Damped Oscillations. See F. W. Peek, Jr., "The Effect of Transient Voltages on Dielectrics," A. I. E. E., TRANS. Vol. XXXIV, 1915, p. 1857.

The high-frequency test has very important uses and also limitations. Its most important use is to locate cracks and flaws in insulators. It will not detect moisture as readily as the 60-cycle test.

All of the tests in general use are devised for locating faults after they occur; they are successfully used for this purpose. There is much need of tests for anticipating deterioration at the factory in order to eliminate the great expense of testing and changing insulators after a year or so of service. The so-called deterioration of porcelain is due to two main causes—gradual absorption of moisture by porus porcelain, and gradual cracking due to mechanical stress of poor design, cement, firing, etc. Failures often result only after several years of service. There is no volatge test in use at present that will anticipate in the factory conditions which will later cause failure on the lines by absorption and cracking. Such conditions may be anticipated, not by high voltage, but by absorption tests, and such mechanical tests as expansion and contraction, etc.

E. E. F. Creighton: I am going to agree immediately with Mr. Peek on one point and get it out of the way, and that is that there is no electrical test known today that will eliminate all defective porcelain. Porcelains are porous from about 1 per cent down to perhaps 0.005 of 1 per cent, as far as we have been able to measure. We have not yet connected up the relation between the test and the porosity, but we have this one very useful, practical result, that the test with the high-frequency oscillator in the factory, where the porcelains come directly from the furnace, and where the oscillator is specially fitted for the test, eliminates on the average about 8 per cent more porcelains than the 60-cycle test.

The man who wants to use the insulators is interested in getting the very last bad one out. The oscillator does not, apparently, take all the bad ones out. There are some of very small porosity which may or may not develop later on into poor insulators by absorbing moisture from the cement. But, at any rate, we can say that the application of the high frequency from the oscillator is one step better than the 60-cycle test. We hope to find some suitable way before long of eliminating the bad insulators immediately after manufacture.

In regard to the other point, the relation of the 60-cycle test to the high-frequency test, as regards the damage possible to insulators. Taking up the illustration that Mr. Peek gave, of an insulator which is just about to fail on the test voltage. In the case of the 60-cycle test voltage, the flash-over takes place in the insulator at about 100 kilovolts, the average is in that neighborhood. If the strength of the insulator is a little bit below that, the insulator will fail. If the puncture voltage of the insulator is above, the insulator will probably be damaged by the test. The 60-cycle test will leave a certain number of defective insulators to be accepted and placed on the line, when the puncture voltage is only a small percentage above the flash-over voltage.

Turning to the oscillator test, on that same insulator the oscillator test will subject it to 120 kilovolts or 130 kilovolts, and there, again, there will be some insulators which will be ready to break down at that potential, which will not quite break down in the time of application, and they will go through as defective insulators, but after they have gone through as defective insulators, they still have a factor of 30 per cent above their flash-over value, and therefore, from the operating man's standpoint, they are a better insulator than those which barely pass the flash-over test at 60 cycles.

I think that is the answer to the criticism of applying voltages which might damage the insulators. The solution of the problem is to make the insulator so perfect that it will have the proper design and will be made of the proper porcelain to have a factor of safety over, say, the 130 kilovolts of applied potential.

As a result of a comparison between the two tests, the 60-cycle and the high-frequency test, in our factory we have given up entirely the 60-cycle test and replaced it with the high-frequency test. Some of the more recent results, especially those obtained by Mr. Hunt, may make it expedient to apply both the 60-cycle and the high-frequency test to the finished insulators.

Presented at a meeting of the Schenectady Section of the American Institute of Electrical Engineers, Schenectady, N. Y., May 4, 1916.

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ILLUMINATION OF THE PANAMA-PACIFIC INTERNATIONAL EXPOSITION

BY W. D'A. RYAN

ABSTRACT OF PAPER

In this paper the author, who was Chief of Illumination for the Panama-Pacific International Exposition in San Francisco, describes the system of lighting adopted for the Exposition, which was generally conceded to have initiated a new era in the art of illumination. From a narrow engineering point of view the lighting would have been regarded as inefficient, but the object striven for was to suppress high intrinsic brilliancy, while bringing out the architectural beauties of the Exposition structures in the most effective manner, bathed in a harmony of color. Many beautiful effects were obtained by the various installations which are described, and one of the most original features was the successful effort to preserve the curvature and detail in relief by the use of lights of different strengths and colors thrown from different or opposite directions upon the same object.

THE illumination of the Panama-Pacific International Exposition was finally classed by the International Jury of Awards as a "decorative art", largely because it appealed to the imagination and feelings of the masses, and carried a message much the same as painting or music, as demonstrated by the happy enticing effect of the heraldic banners on the Avenue of Progress, the deep mystery in the Court of Abundance, the grandeur and uplifting effect of the great candle-fountains in the Court of the Universe, the quiet peaceful illumination in the Court of the Four Seasons and on the Palace of Fine Arts, the Alladin dreams and fairy-like suggestions of the illuminated towers, flags, reflections and other features which made up the lighting as viewed from the South Gardens.

In this connection I wish to quote Edwin Markham's impressions gained on try-out night, February 15, 1915:

"I have tonight seen the greatest revelation of beauty that was ever seen on the earth. I may say this, meaning it literally and with full regard for all that is known of ancient art and architecture, and all that the modern world has heretofore seen of

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Manuscript of this paper was received July 24, 1916.

NOTE: The colored illustrations for this paper were supplied through the courtesy of the Schenectady Section of the American Institute of Electrical Engineers.

glory and grandeur. I have seen beauty that will give the world new standards of art and a joy in loveliness never before reached. This is what I have seen—the courts and buildings of the Panama-Pacific Exposition illuminated at night."

The illumination of the Exposition was based on developments of the science of lighting, and represents results of personal experience in this field extending over a period of twenty years.

The lighting for the Exposition was completely designed in the latter part of 1912 and every feature was carefully calculated, as there was practically no opportunity for trial, owing to the radical nature of the scheme and scope. The buildings of previous expositions had in the main been used as a background upon which to display lamps. The art of incandescent outlining, notably the beautiful effects obtained at the Pan-American Exposition at Buffalo, could probably not be improved upon, and furthermore, this form of lighting had been extended to amusement parks throughout the world and had become commonplace. Its principal disadvantages were the diminution of artistic effectiveness at close range, similarity in effects from different view-points, the suppression or complete obliteration of architectural features, and the economic necessity of extensive untreated surfaces. Furthermore, the glare from so many exposed sources when assembled on white or light-colored buildings, caused severe eye strain.

The lighting scheme and scope of the Panama-Pacific International Exposition called for a radical departure from previous practise. Incandescent outlining on the main group of palaces was avoided, and screened or masked flood and relief lighting to produce the third dimension or depth, substituted, and great care was exercised to preserve the architectural features and color, with proper relative intensities. For the first time at an international exposition, the illuminating sources, whether arcs, incandescent or gas, lost their identity as such. While a uniform system was maintained throughout, each court possessed its individual characteristics with radical differences, and at the same time the transition from one effect to another was harmonious, even to the extent of an intermediate step or carnival effect on the Avenue of Progress connecting the Zone and the main group of palaces.

During the pre-exposition period, there were many who maintained that the general public would not be attracted except by the glare of exposed brilliant sources. The lighting of the Exposition, however, immediately disproved this theory and a strong psychological appeal was made by the highly artistic lighting effects.

During the period elapsing between the Louisiana Purchase Exposition and the Panama-Pacific International Exposition, wonderful advances had been made in the efficiencies of all types of lighting units. This made it possible to illuminate in the main group of buildings, approximately 8,000,000 sq. ft. (743,200 sq. m.) of horizontal and vertical surfaces to an illumination ranging from 1/10 to 1/4 of a foot-candle in the incidental gardens and roadways, from 1/4 to 3 foot-candles in the building facades and adjacent lawns and gardens, and from 5 to 15 foot-candles on the towers, flags and sculptural groups. The lighting load on the main group of buildings, including the window lighting and the scintillator, was approximately 5000 kw. The total connected load for all purposes, including Zone, Foreign and State sections and exhibitors, for light and power, was 13,954 kw., with a maximum peak of 8200 kw. and an average peak of 7880 kw. During the Exposition period of approximately ten months, a total of 16,057,790 kw-hr. was purchased from the Pacific Gas and Electric Company. Of this amount, 5,582,906 kw-hr. were sold to exhibitors and concessionaires, the remaining 10,474,884 kw-hr. being used by the Exposition.

While the lighting of the Exposition was primarily electric, all modern sources of intrinsic merit were used, and a number of excellent gas features were introduced. About four miles of streets in the Foreign and State sections were illuminated with Penn globe high-pressure gas "arcs," in 20-in. (508-mm.) opal globes mounted with their centers about 16 ft. (4.9 m.) above the roadways on ornamental poles spaced approximately 100 ft. (30.5 m.) apart, staggered. The same type of lamp was used for emergency lighting on the kiosks throughout the grounds. Five-mantle Humphrey gas "arcs" enclosed with ornamental lanterns were used in pairs on the standards in the Zone (amusement section) and the same type of lamp, of smaller sizes, furnished emergency lighting at the gates and important exits from the main group of buildings. Gas flambeaux were introduced in the effects in the Court of Abundance and the North Approach. The total gas flow for the purposes mentioned was approximately 15,000 cu. ft. (425 cu. m.) per hour. The average amount of gas consumed daily at the Exposition for all purposes was 486,550 cu. ft. (13,780 cu. m.). The total amount purchased by the Exposition Company during the

Exposition period was 121,913,500 cu. ft. (3,452,590 cu. m). Of this amount only 25,101,496, cu. ft. (710,874 cu. m.) was used by the Exposition Company, the remainder being sold to exhibitors and concessionaires.

In order to obtain a harmonious illumination scheme, it was necessary to visualize the lighting as a whole, and to establish illumination and color values for every part of the Exposition before definite specifications for lighting equipment could be made. The preliminary tests and calculations on lighting units that had been selected for use at the Exposition were made at the Illuminating Engineering Laboratory. The work of calculation was greatly shortened and simplified by the use of various graphical charts, one of which, an illumination chart, is described by Mr. Frank A. Benford, Jr., in the *Transactions* of the Illuminating Engineering Society*. The lighting units were all new developments, in many cases used in new ways. This necessitated a vast amount of preliminary investigation which usually took the form of calculations of the illumination on the grounds, facades and towers. From these calculated values it was possible to determine if the selected lighting units were of the right size and were properly arranged on the preliminary plans. As soon as any particular phase of the lighting was fully decided upon, the illumination and luminous flux values were calculated in all their minute details, so that long before the Exposition opened there were on hand complete sets of illumination diagrams for all the various courts, buildings and towers. Some of these diagrams are illustrated by Figs. 7, 8, 16, 20 and 23, which are referred to later.

The principal features of the lighting are described under their respective headings and illustrated by the accompanying plates.

Luminous Effects in Tower Illumination. This illumination consisted in flood-lighting the towers with a white rising light which created shadows. The shadows were in turn illuminated by concealed colored light on the various stages, thereby producing detail in shadow. This combination gave the structures a luminous effect never before obtained. These towers further illustrated the preservation of depth, or the third dimension in light, which feature predominated throughout the Exposition. The Tower of Jewels was flood-lighted by batteries of arc projectors located on the roofs of the main group of palaces, the

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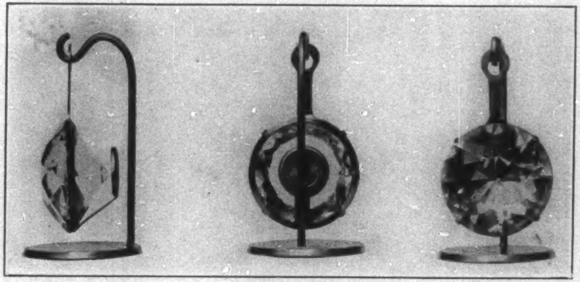
*Vol. VII, page 695, 1912.



[RYAN]

FIG. 1—NOVAGEMS MOUNTED IN BRASS HOLDER

PLATE XVIII.
A. I. E. E.
VOL. XXXV, 1916.

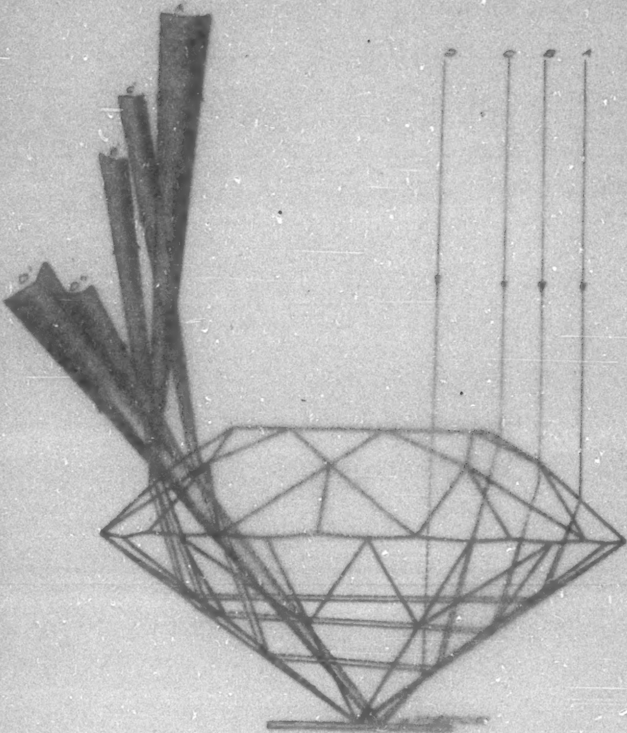
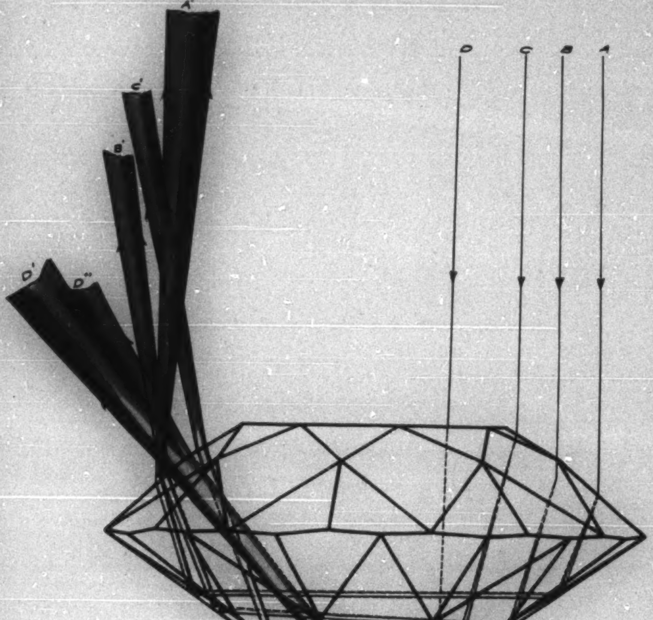


Fig. 2—Breaking Up of Incident Light Passing Through Novagem Jewels


A'
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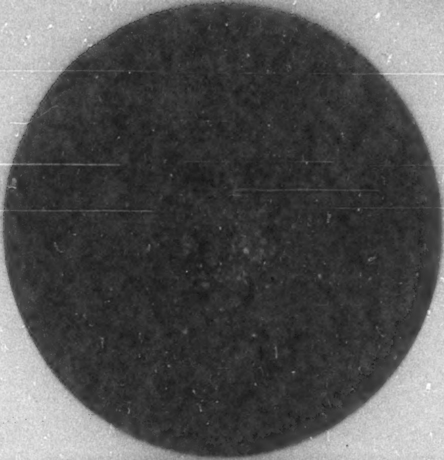


Fig 3—Spectra Produced by Single Beam of Light

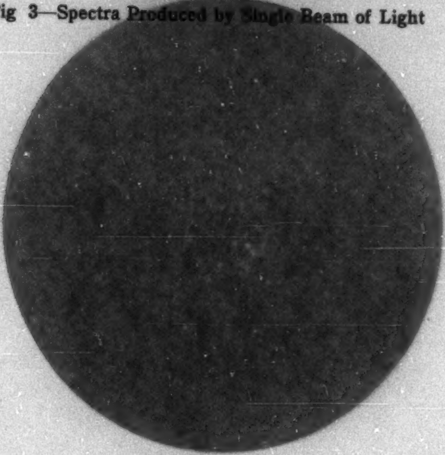
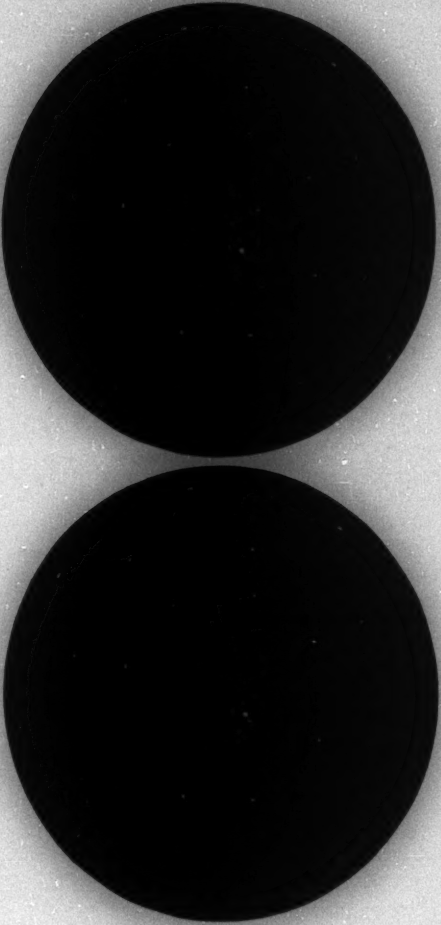


Fig. 3A—Increased Spectra Due to Use of Mirror



South Garden pavilions and the Scott Street entrance gate. In order to obtain the proper gradation of light with an economic distribution, it was necessary to equip the majority of the projectors with properly designed diverging doors. A complete set of color screens at each projector enabled the changing of the color tone of the tower on very short notice. The base section was necessarily carried in the same relative illumination as the building facades. Above this section there was a rising illumination to approximately 20 foot-candles on the top ball. The average value for all levels was 10 foot-candles. The shadows cast by the rising searchlight beams were illuminated by rose red relief lighting. At the top level there were four 30-in. (762-mm.) arc projectors equipped with changeable color screens for spectacular and heightening effects. The twin Italian towers at the entrances to the Courts of Palms and Flowers were lighted in a similar way.

"Novagem" Jewels. "Novagem" jewels are scientifically cut glass of high index of refraction, made to imitate diamonds, rubies, sapphires, emeralds, etc. Each was mounted in a suspension carrying a mirror at the apex of the stone, which increased the spectra approximately forty per cent. These jewels were used to carry architectural lines in addition to being massed on shields and other points. They were mounted in such a way that they were kept in motion by the wind, thereby adding action to the effect when illuminated with projected light, which, especially in the white stones, produced all the colors of the spectrum with unusual purity. 102,000 47-mm. diameter jewels were used on the Tower of Jewels, and about 4000, in sizes from 21 to 47 mm., were hung on the star heads of the seraphic figures in the Court of the Universe. Fig. 1 shows one of the novagems mounted in the brass holder. Fig. 2 illustrates the breaking up of the incident light passing through one of the 47-mm. stones. Fig. 3 is a reproduced from a photograph of the spectra produced by a single beam projected normal to the plane of the table. Fig. 3A shows the increased spectra due to the use of the mirror.

The following table gives the indices of refraction, specific gravity and weight of the 47-mm. stones:

Indices	Specific gravity	Weight, 47-mm.
Yellow..........1.669	3.925	0.235 lb. avoir.
White..........1.616	3.589	0.221 lb. "
Pink............1.618	3.595	0.216 lb. "
Ruby...........1.618	3.87	0.237 lb. "
Amethyst.......1.616	3.55	0.234 lb. "

The Electric-Steam Color Scintillator. The scintillator consisted of combining searchlights in systematic drill in colored and white beams with smoke and steam, so as to produce spectacular effects or fireless fireworks, both aerial and on the ground, possessing artistic color combinations and blendings impossible with ordinary fireworks. This was further enhanced by the running of a large express locomotive at high speed under brake so as to produce large volumes of smoke and steam which were illuminated in color. Other steam effects were in the form of fans, plumes, wheels, fighting serpents, etc. This battery was composed of 48 36-in. (914-mm.) hand-controlled arc projectors. They

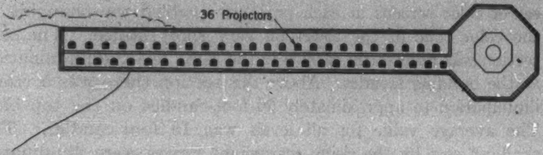


FIG 4—ELECTRIC COLOR SCINTILLATOR

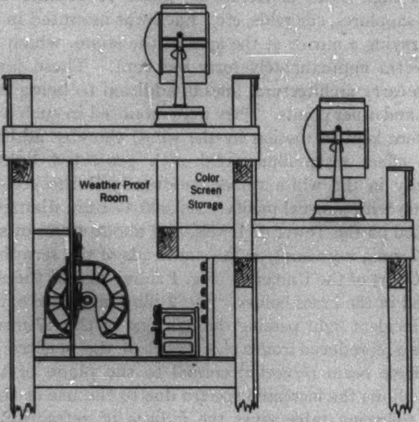


FIG. 5 — CROSS SECTION OF ELECTRIC COLOR SCINTILLATOR

were operated at nominal 110 volts, 110 amperes, and with the resistance consumed a total of 581 kw. The beam candle power of each was approximately 55,000,000, or an aggregate of 2,640,000,000 for the battery. With the equipment of each projector was a set of seven colored gelatine screens, treated with spar varnish and turpentine as a protection against moisture.

These searchlights were located on the double deck pier on the north breakwater of the yacht harbor (Fig. 4), which was constructed as shown by the cross-section drawing (Fig. 5). Part of the space below the upper deck was used for housing the color screens, resistance boxes and distribution system, as well as a 250-kw. motor-generator set (see photographs) which supplied part of the power for the projectors. The remainder of the power necessary was taken from a 1000-kw. set located in the Palace of Liberal Arts.

The locomotive, steam apparatus and fireworks mortars were located on the south breakwater of the yacht harbor (Fig. 6).

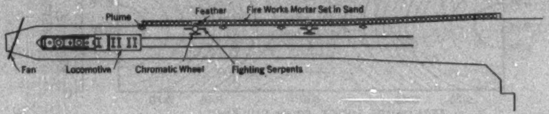
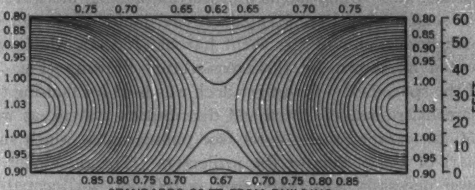


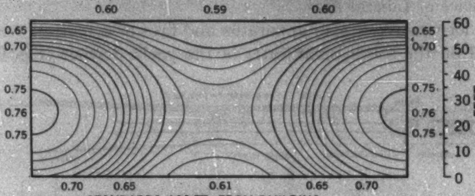
FIG. 6—STEAM SECTION OF ELECTRIC STEAM COLOR SCINTILLATOR

In addition to supplying the various steam effects such as plumes, chromatic wheels, fairy feathers, etc., this locomotive, which was a modern Southern Pacific oil-burning passenger type, was blocked up and locked so that the wheels could be driven at a speed of 60 miles (97 km.) per hour under brake. Thus great volumes of steam and smoke were produced, which, when illiminated with various colors, created a wonderful spectacle.

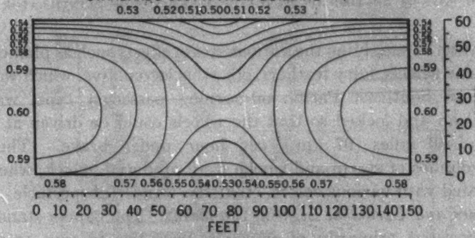
Banner and Cartouche Lighting Standards. The banner standards consisted primarily of anywhere from two to nine ornamental luminous arcs mounted on 25- to 55-ft. (17- to 7.6-m.) shafts, the lamps being screened by banners in such a way that they flood-lighted the buildings, lawns, trees and shrubbery, and at the same time, the direct source was not visible in the main vistas. These banners, which formed decorations by day and beautiful spots of color by night, were hung so that they moved in the wind, adding action to the effect. At the same time, they were weighted and guided in such a manner that they did not expose the source or become self-destructive by whipping. As a matter of further interest, the history of California and the Pacific ocean was written in the designs on the three-, five- and seven-light banners, by the use of the heraldic shields of the early explorers and pioneers. The banner standards were used for flood-lighting the Court of the Four Seasons, the Palace of Horticulture, Festival Hall, all palaces fronting on the Avenue of Progress, and the central group on the Avenue of Palms.



STANDARDS 80 FT. FROM BUILDING



STANDARDS 100 FT. FROM BUILDING



STANDARDS 120 FT. FROM BUILDING

FIG. 7—ILLUMINATION ON EXTERIOR OF BUILDINGS—FIVE LIGHT STANDARDS

Light reflected from banners adds 20 per cent to the above values

The three isolux diagrams shown in Fig. 7 give the foot-candle values obtained in preliminary calculations for the illumination of the exterior facades of the main group and furnished a basis for estimating the number of lamps required for general surface illumination. Fig. 8 shows a preliminary curve of foot-candle values calculated for the building facades within the Court of the Four Seasons. The photometric test values taken under operating conditions checked very closely with these original calculated values.

The cartouche standard was of the same order as the banner standards, except that painted translucent fabric was used in place of canvas, which was not free to move, being held rigidly in the cartouche. In addition to screening the direct light from the people, it created pleasing spots of color in contrast with the walls of the buildings and supplemented, with the banner standards, the flag illumination or sky line effect.

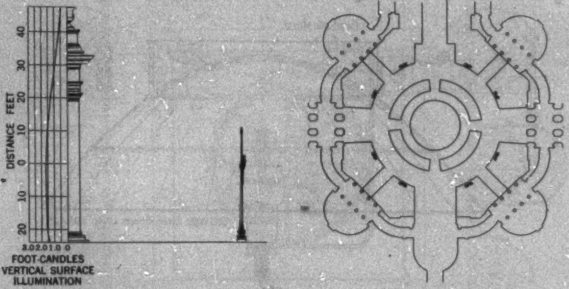


FIG. 8—VERTICAL SURFACE ILLUMINATION—COURT OF THE FOUR SEASONS

The flags on the buildings fronting on the Avenues of Palms and Progress were individually lighted by 13-in. (33-cm.) arc projectors, 100 units being used for this purpose. Economic reasons necessitated the designing of an incandescent projector for the lighting of the flags on the north and west walls and in the courts. This unit (Fig. 9) was constructed of an 11-in. (28-cm.) diameter parabolic mirror surrounded by a double row of small plain mirror panels which extended the parabola, thus increasing the efficiency. Two hundred projectors of this type with 500-watt mazda stereopticon lamps were used.

Electric Kaleidoscope. The electric kaleidoscope was designed to create exterior effects on the glass dome of the Palace of Horticulture, such as revolving bars, rings and spots in astronomical movements or the dissolving of colors from one shade or tint to another, without a sharp line of demarcation.

It consisted primarily of a battery of twelve 30-in. (762-mm.) arc projectors, arranged around a central structure as shown in the plan view, Fig. 10. The light from these twelve projectors passed through a common orifice in the top platform of the structure, at which point were located specially cut revolving interchangeable lenses. Before passing through the lenses the projected beams of light were intercepted by revolving color screens and shadow bars. Each one of these units was operated by an individual mechanism and independently of one another, as shown by the photographic and elevational view in Figs. 11 and 12. The different types of lenses were made up in sets of four separate quadrants (Fig. 13), which permitted the use of any combination of lenses desired at the same time. With this flexibility of lens combinations, together with the interchangeable color screens and shadow bars, it was possible to obtain a variety of effects.

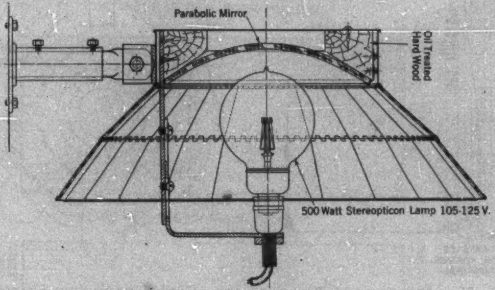


Fig.—9 Flag Lighting Unit

N. B. The glass in the dome of the Palace of Horticulture was not in accordance with specifications. The results, while generally satisfactory, could not come up to anticipations, due to the lack of sufficient diffusion in the glass.

Indirect Lighting for Large Auditoriums. This lighting is applicable to large auditoriums or large places where concealed lighting is desired, but where the dome or ceiling construction does not permit the use of it. The system consists of placing a battery of searchlights beneath the main floor and concentrating the beams on a diffusing plate in a central screened opening for re-distribution to the ceiling.

This was demonstrated by the installation in Festival Hall before the building was converted into a theater. Twelve 18-in. (457-mm.) projectors were used, giving a combined beam candle power of approximately 114,000,000. Inasmuch as a large city sewer ran directly underneath the center of the building, it was necessary to locate the projectors in respect to it, as shown in Figs. 14 and 15. Fig. 16 shows a preliminary calculated illumination curve for the ceiling and walls.

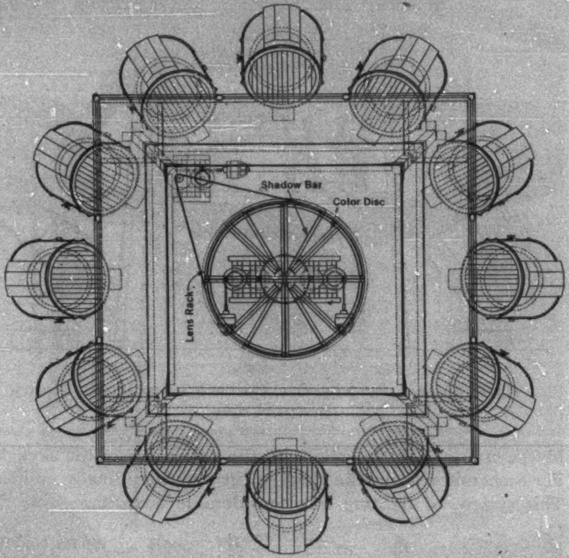


FIG. 10—PLAN VIEW OF ELECTRIC KALEIDOSCOPE—PALACE OF HORTICULTURE

Non-Glare Art Gallery Illumination. In the lighting of the Palace of Fine Arts a system was designed whereby the lamps were placed above the skylight and around the perimeter. By the combination of a suitable angle reflector and the proper diffusion glass a good general distribution was obtained on the hanging surfaces, and specular reflection was further reduced by the use of shadow curtains on the under side of the skylight. For economic reasons the shadow curtains were finally omitted. This system of lighting has considerable advantage over the common practise of distributing lights generally over the skylight, which produces strong specular reflection and also gives the greatest illumination on the floor in the center of the room, where it is least desired.

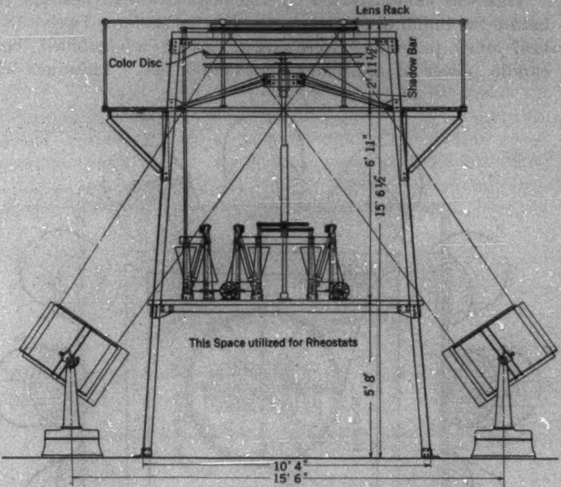

Lens Rack
Color Disc
Shadow Bar
2' 11½"
6' 11"
15' 6½"
This Space utilized for Rheostats
5' 8"
10' 4"
15' 6"

Fig. 11—Elevation of Electric Color Kaleidoscope—Palace of Horticulture

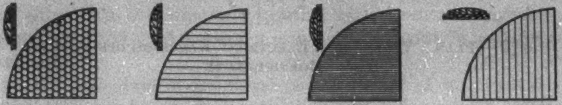


Fig. 13—Lens Quadrants for Electric Kaleidoscope—Palace of Horticulture

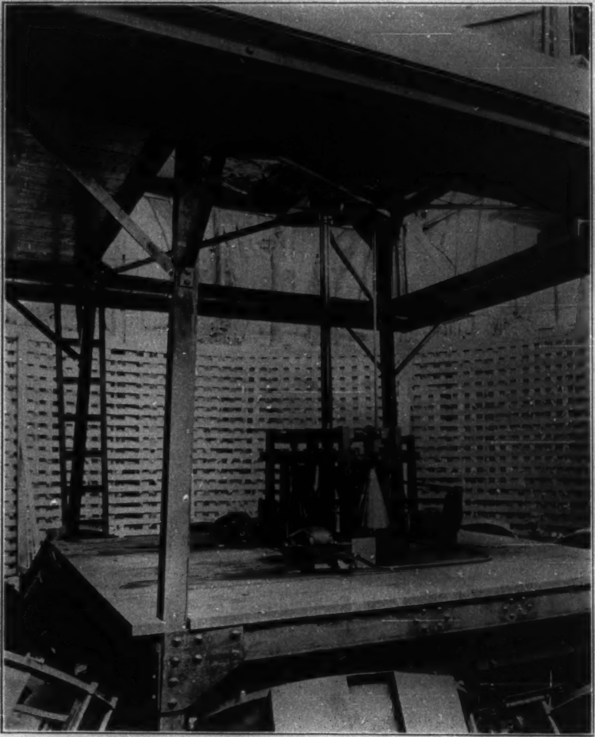


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FIG. 12—ELECTRIC COLOR KALEIDOSCOPE, PALACE OF HORTICULTURE

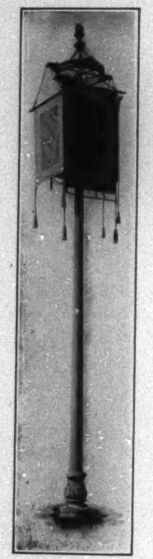

FIG. 26—FRONT VIEW OF FIVE AND SEVEN-LIGHT LUMINOUS ARC LAMP BANNER STANDARD—HEIGHT 35 FEET

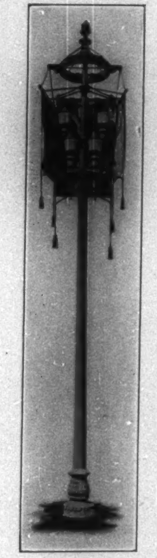

FIG. 27—REAR VIEW OF FIVE-LIGHT LUMINOUS ARC LAMP BANNER STANDARD, HEIGHT, 35 FEET

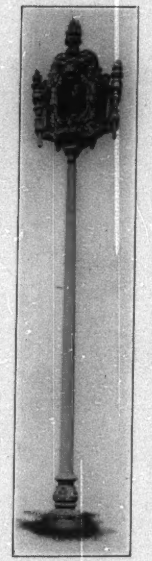

FIG. 28—THREE-LIGHT LUMINOUS ARC LAMP CARTOUCHE STANDARD, HEIGHT 35 FEET

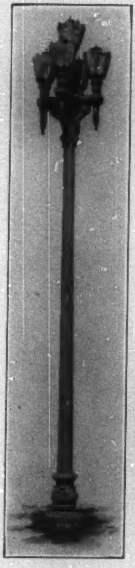

FIG. 29—FIVE LIGHT LUMINOUS ARC LAMP BAND CONCOURSE STANDARD, HEIGHT 35 FEET

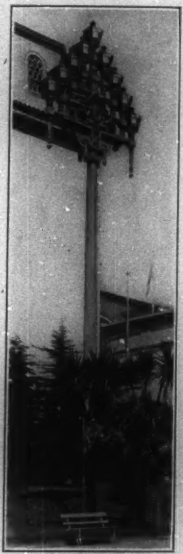

FIG. 30—NINE-LIGHT LUMINOUS ARC STANDARD, HEIGHT 35 FEET

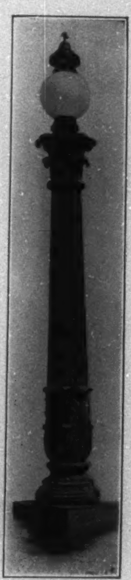

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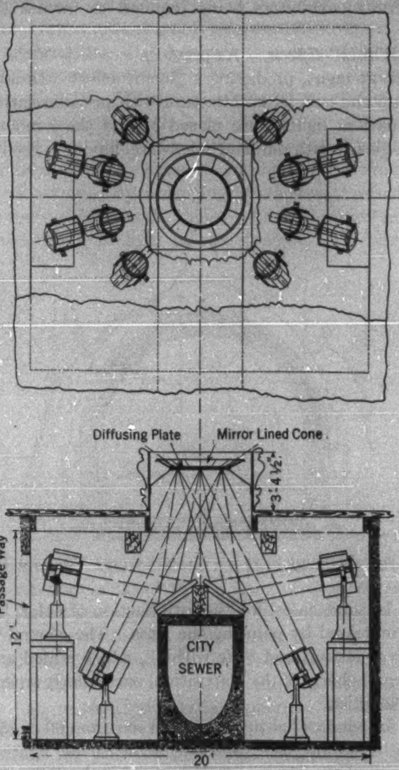
FIG. 31—MARINA TYPE PENN GLOBE HIGH PRESSURE GAS ARC STANDARD

High Bay Lighting. For the illumination of high bays, large units, singly or in pairs, were placed at the maximum height in special reflectors (Fig. 17), designed to prevent waste illumination on vertical surfaces and obtain maximum intensity on the floor with relatively uniform distribution, and absence of spots. The main buildings of the Exposition were lighted in this way, using only one-tenth watt per square foot with the mazda


Diffusing Plate
Mirror Lined Cone
3'-4½"
Passage Way
12'
CITY SEWER
20'

FIGS. 14 AND 15—PLAN OF INDIRECT LIGHTING—FESTIVAL HALL

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916

B lamps, resulting in approximately one-half foot-candle average illumination for lamp heights, in some cases over 100 ft. (30.5 m.) above the floor. This illumination was primarily for janitor and police service, exhibitors being required to furnish their own lighting.

"Life Within" Effects. At previous expositions the windows were dark at night, producing a gloomy effect. In addition to lighting up the general architecture with proper relative values of illumination, lights were placed behind the windows which had been glazed with diffusing glassware, having a good daylight texture. In some cases, for the introduction of color, the diffusion was increased by painting the glass. The general effect at night was of festivity, of "life within", which added animation to the general charm of the Exposition, particularly when viewed from an elevation.

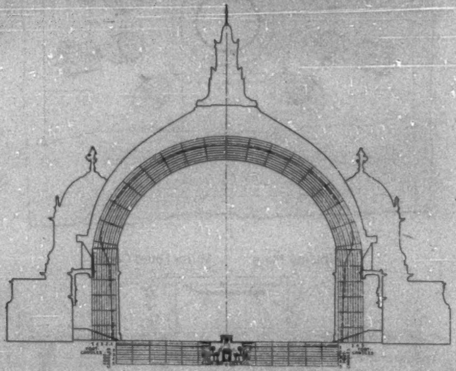


FIG. 16—INTERIOR SURFACE ILLUMINATION—FESTIVAL HALL

Lamps for window lighting ranged in size from 60 to 250 watts, depending upon the size of the window to be lighted. The clerestory windows which were unpainted, were lighted by 150-watt lamps dipped in orange lacquer. Practically all of the entrance windows were painted, and these were illuminated by clear lamps in sheet tin extensive reflectors. All of the window lights, with the exception of those in the domes, were suspended on drop cords. The dome windows were lighted by 250-watt lamps in angle reflectors mounted five feet to the rear of the windows.

Combination Fountain and Light Sources. The original fountains of the Rising and Setting Sun, in the Court of the Universe, designed by McKim, Mead and White, were 65 ft. (20 m.) high. In order to accommodate the lighting the architects increased the height to approximately 95 ft. (29 m.) and constructed them as shown in Fig. 18. The flutes of the 31-ft. (9.4-m.) section beginning at a point 37 ft. (11.3 m.) above the ground surface, were made of ¼-in. (6.35-mm.) thick special diffusing glass, backed up by a secondary sheet of sand-blasted glass to eliminate structural shadows. By arranging 96 1500-watt mazda lamps in twelve rows of eight each, this section of the fountain became an immense candle or light source at night. To dissipate the heat generated by this bank of lamps, consuming 144 kw., a 5-h.p. blower was installed in the base of each fountain and created a forced cooling draft which was discharged from air vents at the base of the ball surmounting the shaft. This ball was lighted from the inside by eight 250-watt mazda lamps. Notwithstanding the fact that the 96 lamps in each one of these fountains had a combined initial spherical candle power of approximately one quarter of a million, the intrinsic brilliancy was relatively low and did not cause disagreeable eye strain. The horizontal and vertical surfaces illuminated by the two fountains were approximately one-half million square feet (46,450 sq. m.).

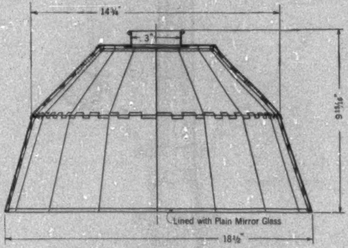


Fig. 17—High Bay Reflector

To carry out the night effect of these fountains, the figure surmounting the glass ball was lighted by two 6-volt, 108-watt incandescent spot-lights located on the roofs of the adjoining

Vol. 35
1916

buildings. The sculptured friezes above the two basins were lighted by twenty-four 150-watt lamps in weatherproof solid body angular reflectors submerged in each basin (Fig. 19). The isolux chart in Fig. 20 shows the initial calculated values for the Court of the Universe and the North Approach. The isolux curves shown in the court proper were calculated from the initial candle power values of the 1500-watt lamps in the fountains. Subsequently, for economic reasons, the illumination was reduced by lowering the voltage on the lamps in order to lengthen their life. The approach to this court was lighted by sixteen 1500-watt lamps, installed in a shell design type of standard. These standards were located on the balustrade

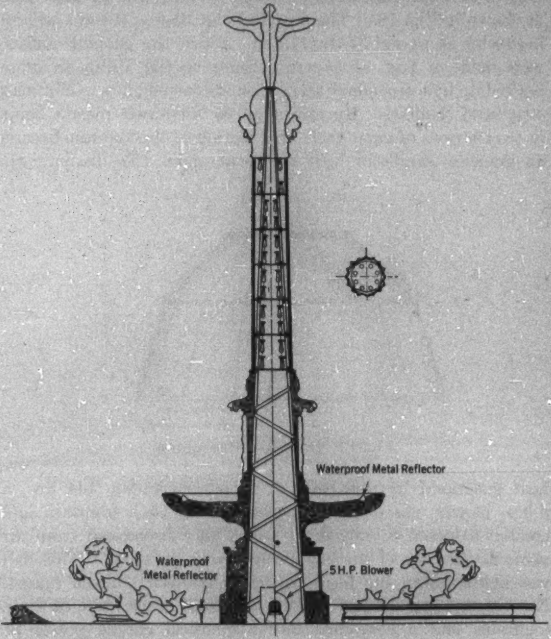


Fig. 18—Elevation of Fountain in the Court of the Universe

surrounding the central pool and flood-lighted the building facade, the promenade receiving most of the light by reflection from the large columns and the overhanging cornice.

Relief Wall Lighting by Concealed Sources. The practise of past expositions has been to place exposed lamps on the rear of the columns to light the back walls. This resulted in lines of light being visible from almost any point of view, which detracted from the appearance of the columns.

In the lighting of the colonnades in the Court of the Universe and the Court of the Four Seasons, three column cups were sunk into the central flute in the rear of each column, in the case of the former, and on the center line of the plain columns in the latter case. These column cups were of pressed opal glass and embedded in the columns (Fig. 21) and spaced 10, 22 and 34 ft. (3.05, 6.7 and 10.4 m.), respectively, above the floor level of the colonnade. Fig. 22 shows the distribution characteristics of this type of cup with a 150-watt clear mazda lamp. The walls were illuminated with a rising light resulting in a total absence of specular reflection and an average illumination on the wall surface of approximately 4 foot-candles. The illumination curve (Fig. 23) shows the values obtained on a vertical line directly back of one of the columns and curve *a-a*, Fig. 20, shows the calculated illumination on a horizontal line along the wall

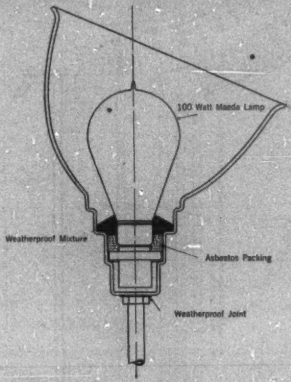


FIG. 19—CROSS SECTION OF ANGULAR WEATHER-PROOFED REFLECTOR

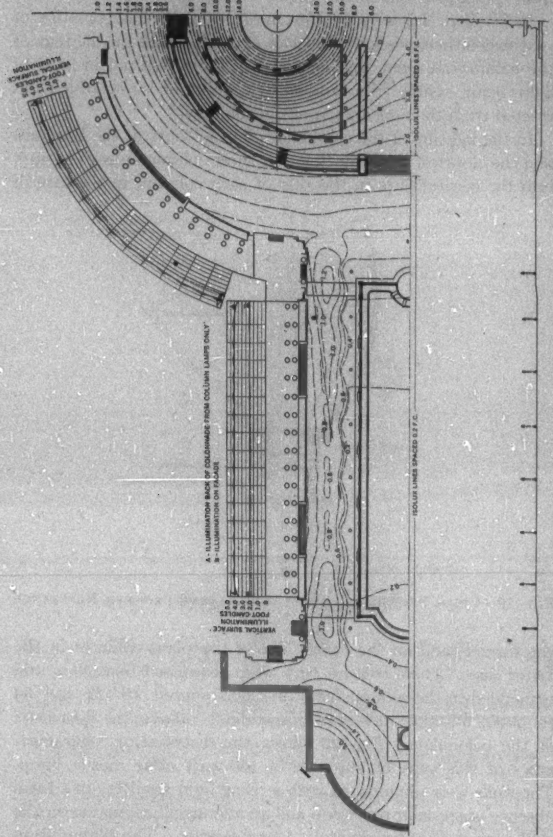

ISOLUX LINES SPACED 0.5 F.C.
ISOLUX LINES SPACED 0.2 F.C.
A - ILLUMINATION BACK OF COLONNADE FROM COLUMN LAMPS ONLY
B - ILLUMINATION ON FACADE
VERTICAL SURFACE ILLUMINATION FOOT-CANDLES
VERTICAL SURFACE ILLUMINATION FOOT-CANDLES

FIG. 20—ISOLUX AND ILLUMINATION DIAGRAM—COURT OF THE UNIVERSE AND NORTH APPROACH

surface 6 ft. (183 cm.) above the floor level. While the column cups were invisible from any part of the court proper, when viewed from the rear of the colonnade they appeared like great drops of molten metal, producing an unusual effect.

The Creation of Mystery in the Lighting of Open Courts. In designing the Court of Abundance, the architect wished to impress as far as possible a feeling of mystery, or something carrying the mind down through the ages. This effect was strengthened by a harmonious blending of illumination by searchlights, incandescent lights, gas flambeaux and illuminated steam.

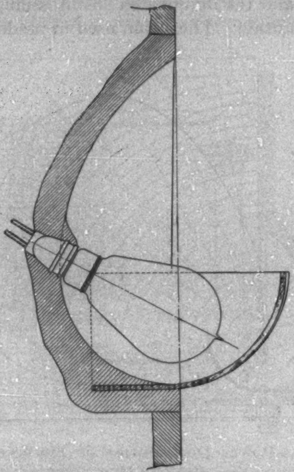


FIG. 21—CROSS SECTION OF COLUMN CUP

The general illumination of this court came from three sources: the snow crystal standards, the cloister lanterns and the gas flambeaux. The snow crystal standard, or as it was sometimes called, the "sunburst" (because of the design suggestion), contained over 600 15-watt round globe orange-dipped incandescent lamps. There were two of these standards in the main court and four in the north approach to this court. On either side and at the spring line of each cloister arch there was suspended a

Gothic lantern with orange glass panels. In addition to lighting the cloister and the adjacent gardens these lanterns were especially valuable for their decorativeness. The gas flambeaux were formed by four rising serpents hissing fire into a flaming caldron. There were six of these located in the court proper and sixteen in the north approach to the court.

The additional "effect" lighting came from the boiling steam-electric caldrons flanking the east and west entrances, the steam-electric torches of the organ tower, the flood and relief lighting of this tower and the illuminated steam issuing from the ball of the central fountain. The steam used in producing these effects was delivered by a 15-h.p. gas-fired boiler located in the base of the organ tower. The color tone of the court at night ranged from orange to rose red.

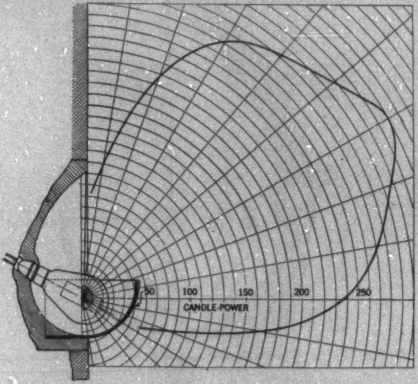


Fig. 22—Candle-Power Distribution of 150-Watt Mazda Lamp in Column Cup

Flood and Relief Lighting to Obtain Artistic Reflections. In order to create reflections of unusual beauty, especially in the illumination of the Palace of Fine Arts, banks of searchlights with diverging doors of varying degrees, designed to meet the requirements, were used to flood-light the building, producing what might popularly be called "triple moonlight". This was supplemented by concealed yellow incandescent light in the soffits of the cornices to the rear of the columns, thereby providing three effects: flood lighting, relief lighting, or the com bination of both. Variety was obtained for special occasions by the introduction of color into the searchlight beams.

Concealed Cascade Lighting. In the lighting of cascades at previous expositions, either the source has been visible, or a reflection of the source, which is equally undesirable. The cascades in the Court of the Four Seasons were so illuminated that neither the light sources nor their images in the water were visible. By the use of green light on the rear surface and red and orange on the front, the effect of iridescence was produced.

Preservation of Curvature and Detail in Relief. The preservation of the curvature and detail in relief was accomplished by lights of different strengths and colors thrown from different or opposite directions on the same object. For example, to preserve the curvature of the walls and the relief of the figures in the four season niches of the Court of Four Seasons, 50 100-watt mazda lamps ranging from red to canary, in metal reflectors, were installed on the top rear side of the niche colonnade (Fig. 24).

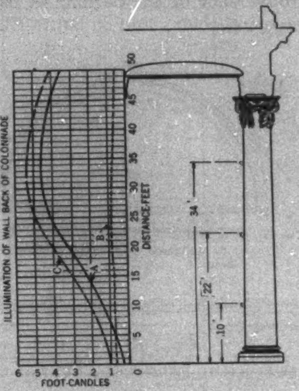


FIG. 23—COURT OF FOUR SEASONS—COLONNADE WALL ILLUMINATION
A—150-watt Mazda lamps in column cups. *B*—2-light luminous arc banner standards. *C*—Column cups and banner standards.

The main arches throughout the Exposition were lighted with concealed red light on one side and pale lemon yellow on the other. All of the lamps used in any one arch were of the same initial candle power, but, due to the difference in absorption of the two colors, the light from one side was of much greater intensity than from the other, thereby preserving the curvature and depth in relief.

Changeability of Lighting Effects. Three-hundred and seventy-three arc searchlights, ranging in size from 13 to 36 in. (33 to 91.4 cm.), were used throughout the Exposition, and 450 concentrated-filament mazda searchlights, forming a so-called "mosquito fleet", were also employed. By the use of colored gelatine screens, it was an easy matter on short notice to change the entire aspect of the Exposition by coloring the lights on the flags, towers and buildings (flooded with searchlights) as well as the rays of the scintillator. For instance, on the 17th of March, the Exposition, including the canopy above, was illumined in green tones; on Orange Day, orange prevailed; on the "Nine Years After" anniversary of the burning of San Francisco, red was the predominating color; and on Santa Clara Day, red and white, the colors of the university, were used—thereby making it possible for the first time to introduce considerable variety on short notice, and at nominal expense, into the illumination effects of an international exposition.

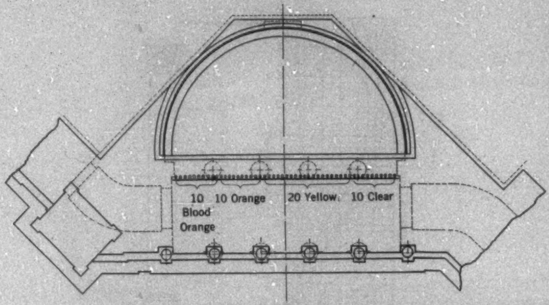


FIG. 24—SEASON NICHE LIGHTING—COURT OF FOUR SEASONS

In conclusion, the lighting consisted primarily of direct, masked, concealed and projected effects, created by a harmonious blending of luminous arcs, searchlights, mazda lamps and gas lights.

The high-current luminous arc lamp was selected for general flood lighting of the facades, lawns and shrubbery, on account of the white quality, high efficiency and relatively low maintenance cost where great quantities of light were required.

The searchlights were used for illuminating towers and minarets, flags and other features where concentration and high intensity were necessary.

Mazda lamps, in all sizes from 10 to 1500 watts, were employed generally throughout the Exposition, especially where space was limited, where warm, normal tones were required and flexibility was of fundamental importance.

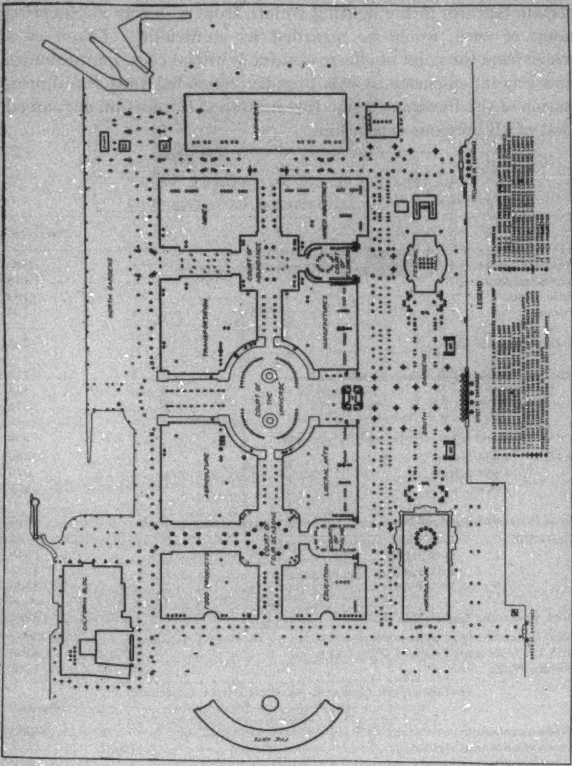

MACHINERY
MINES
VARIED INDUSTRIES
COURT OF ABUNDANCE
COURT OF FLOWERS
TRANSPORTATION
MANUFACTURES
COURT OF THE UNIVERSE
AGRICULTURE
LIBERAL ARTS
COURT OF FOUR SEASONS
COURT OF PALMS
FOOD PRODUCTS
EDUCATION
CALIFORNIA BLDG.
NORTH GARDENS
SOUTH GARDENS
FESTIVAL
HORTICULTURE
FINE ARTS
LEGEND

FIG. 25—GROUND AND BUILDING PLAN OF MAIN EXHIBIT PALACES
Showing Location of Incandescent and Arc Standards, Gas Emergency Lights and Searchlights

High-pressure gas lighting played an important part in street lighting in the Foreign and State sections, low-pressure gas for emergency purposes, and gas flambeaux for special effects.

The unusual consideration given to esthetics and the suppression of high intrinsic brilliancy effects, naturally introduced certain features in the lighting which, from a purely engineering point of view, would be regarded as inefficient. Taken as a whole from the point of effects obtained, initial cost, maintenance and general efficiency, it was broadly conceded that the illumination of the Panama-Pacific International Exposition surpassed that of all previous expositions.

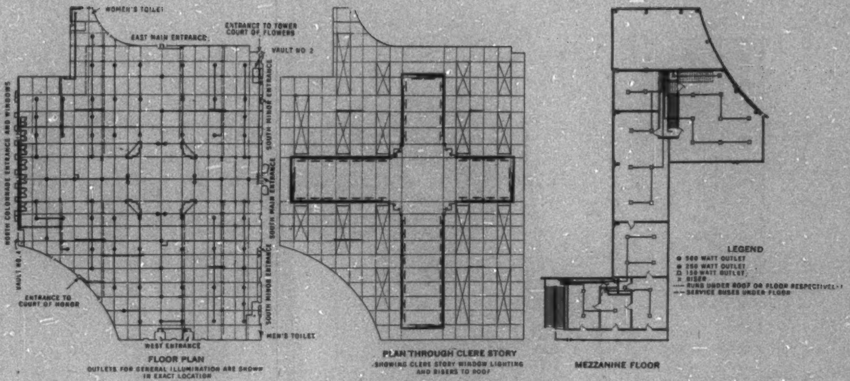
GENERAL LIGHTING AND POWER DATA

PANAMA-PACIFIC INTERNATIONAL EXPOSITION—1915

		Total kw.
Incandescents installed and operated by Exposition Co. (approx.)		3650
Luminous Arcs " " " " " "		548
Searchlights " " " " " "		1792
Pumps " " " " " "		750
Total Power and Light " " " " "		6740
State and Foreign Buildings	Light inside	716
" " " "	Light outside	134
" " " "	Power	75
Total Power and Light—States and Foreign Sites		925
ZONE	Light inside	1352
	Light outside	676
	Power	875
Total Power and Light—Zone		2903
EXHIBITORS	D-C. Light	45
	D-C. Power	618
	A-C. Light	1293
	A-C. Power	1430
Total Power and Light—Exhibitors		3386
Total Connected Load at Exposition		13954
Peak Load, occurred February 20th, 7:45 p. m.		8200
Average Peak		7880

INSTALLED AND OPERATED BY EXPOSITION COMPANY

	Number
Mazda incandescent outlets (approx.)	35000
Mazda incandescent standards	588
6.6-ampere ornamental luminous arcs	800
Luminous arc standards	208
High-pressure gas "arcs"	275
" " " (standards)	205
Low-pressure gas lamps	232
Searchlights (100 13-in.; 200 18-in.; 25 30-in.; 48 36-in.)	373
Total pieces of illuminating glassware (approx.)	5000


WOMEN'S TOILET
EAST MAIN ENTRANCE
ENTRANCE TO TOWER
COURT OF FLOWERS
VAULT NO 2
SOUTH MINOR ENTRANCE
SOUTH MAIN ENTRANCE
SOUTH MINOR ENTRANCE
MEN'S TOILET
WEST ENTRANCE
NORTH COLONNADE ENTRANCE AND WINDOWS
VAULT NO. 4
ENTRANCE TO
COURT OF HONOR
LEGEND
● 500 WATT OUTLET
● 250 WATT OUTLET
◻ 150 WATT OUTLET
x RISER
— RUNS UNDER ROOF OR FLOOR RESPECTIVELY
-- SERVICE BUSES UNDER FLOOR

FLOOR PLAN
OUTLETS FOR GENERAL ILLUMINATION ARE SHOWN
IN EXACT LOCATION

PLAN THROUGH CLERE STORY
SHOWING CLERE STORY WINDOW LIGHTING
AND RISERS TO ROOF

MEZZANINE FLOOR

FIG. 32—OUTLET AND WIRING DIAGRAM—PALACE OF MANUFACTURES

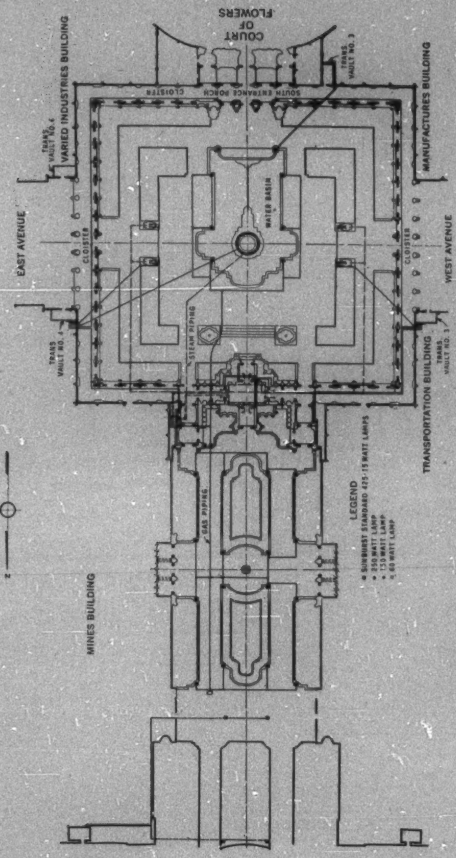
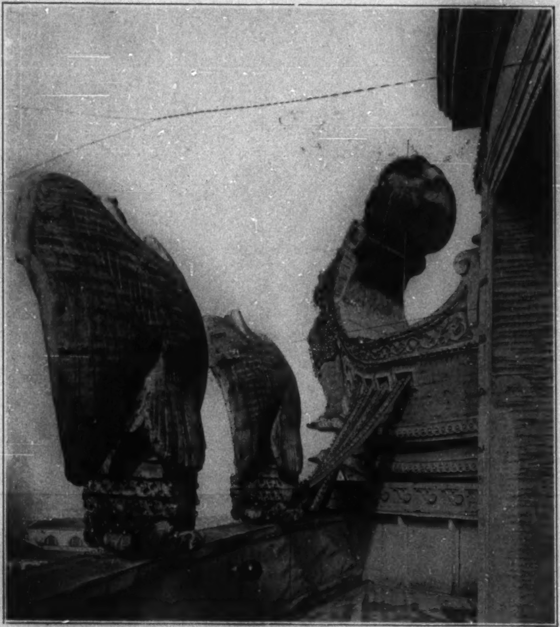

COURT OF FLOWERS
VARIED INDUSTRIES BUILDING
MANUFACTURES BUILDING
TRANS. VAULT NO. 6
TRANS. VAULT NO. 3
CLOISTER
SOUTH ENTRANCE PORCH
CLOISTER
EAST AVENUE
CLOISTER
WATER BASIN
CLOISTER
WEST AVENUE
STEAM PIPING
TRANS. VAULT NO. 4
TRANSPORTATION BUILDING
TRANS. VAULT NO. 1
GAS PIPING
LEGEND
● SUNBURST STANDARD 425-15 WATT LAMPS
• 250 WATT LAMP
• 150 WATT LAMP
• 60 WATT LAMP
MINES BUILDING
N

FIG. 33—OUTLET, WIRING, STEAM AND GAS DIAGRAM—COURT OF ABUNDANCE



[RYAN]

FIG. 34—VIEW OF TOWER OF JEWELS SHOWING METHOD OF SUSPENDING JEWELS AND RED LAMP FOR RELIEF LIGHTING

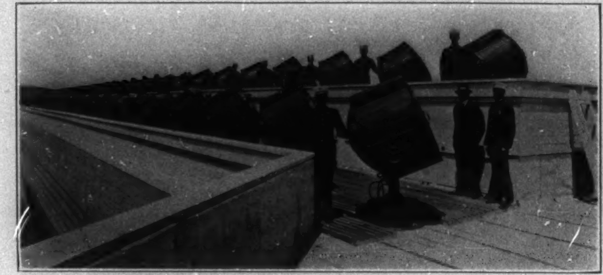
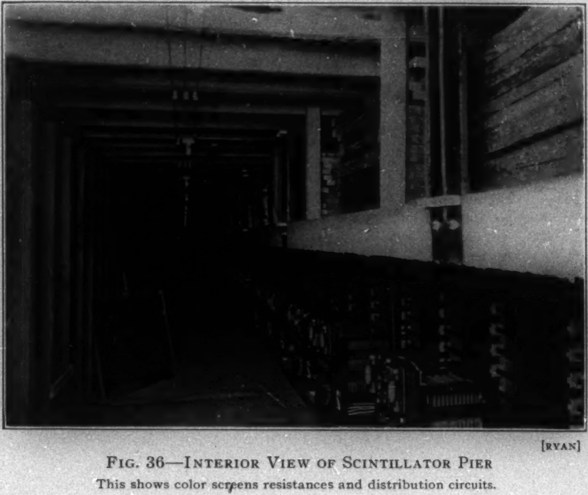


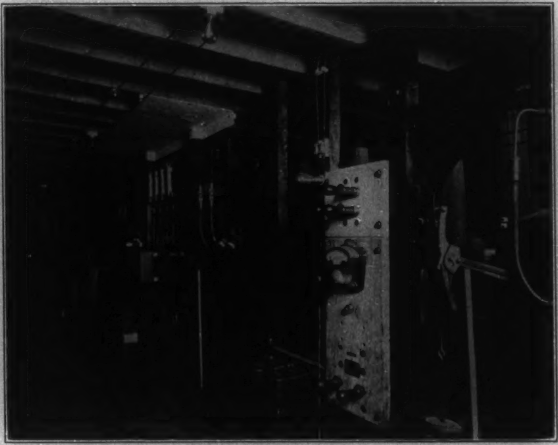
FIG. 35—ELECTRIC—COLOR—STEAM—SCINTILLATOR



[RYAN]

FIG. 36—INTERIOR VIEW OF SCINTILLATOR PIER

This shows color screens resistances and distribution circuits.



[RYAN]

FIG. 37—INTERIOR VIEW OF SCINTILLATOR PIER

This shows motor-generator set with station apparatus.

PLATE XXVI.
A. I. E. E.
VOL. XXXV, 1916.

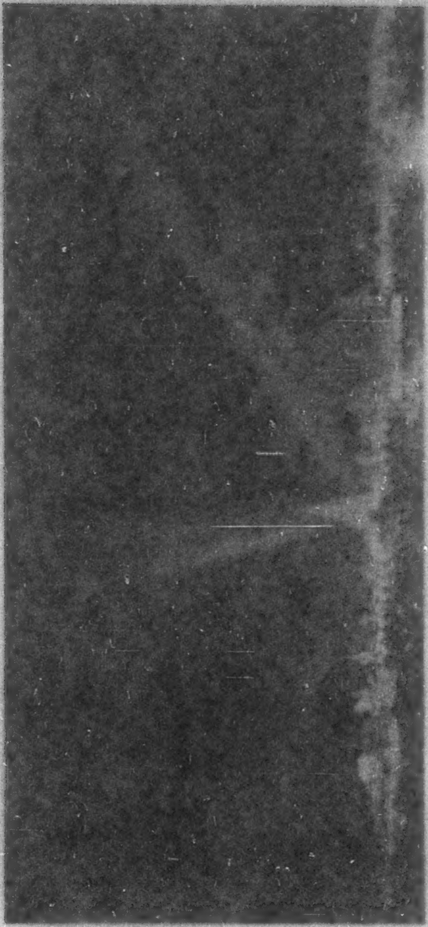


Fig. 38—Panoramic View from Fillmore Hill

Vol
191

Fig. 59—Street Lighting—States and Foreign Sites

Approximately four miles of streets in this section were illuminated by 306 Penn Globe ornamental high pressure gas arcs

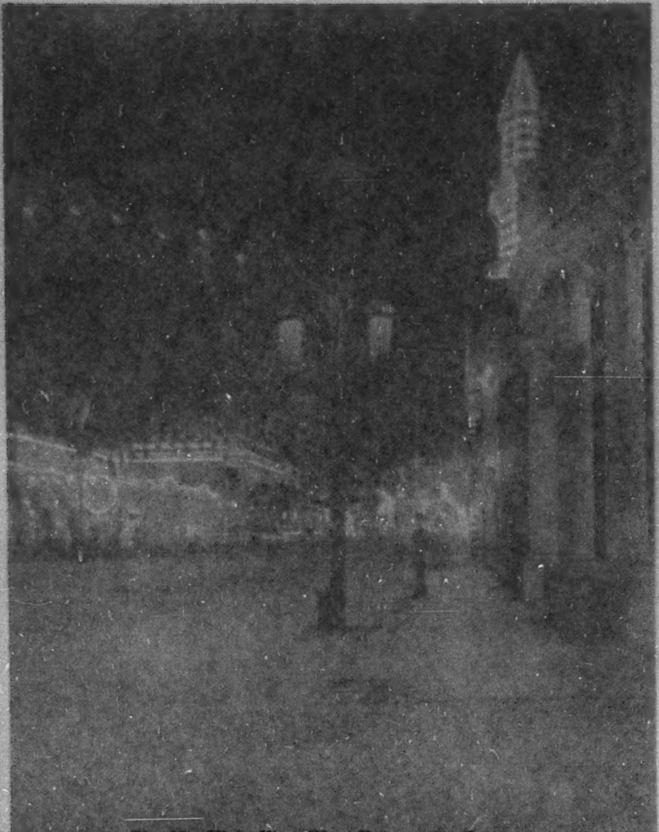
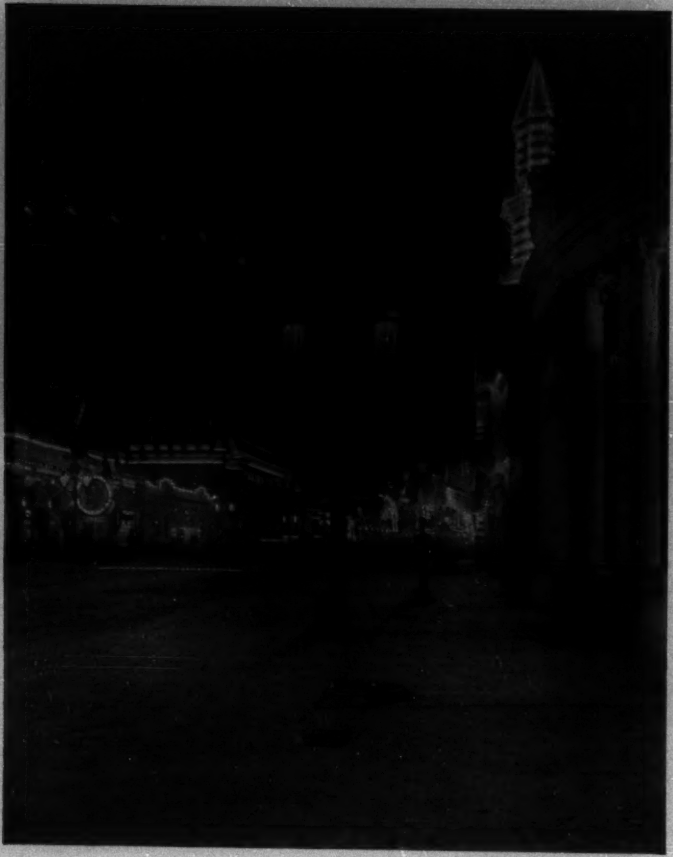


Fig. 40—Night View West Entrance to Zone

In addition to the concessionaires' usual outline lighting, the exposition company maintained a combination system consisting of five-light Humphrey gas arcs in ornamental lanterns and in pairs tied together by an arch of Mazda lamps with star-shaped triple reflectors supporting red ribbon festoons.



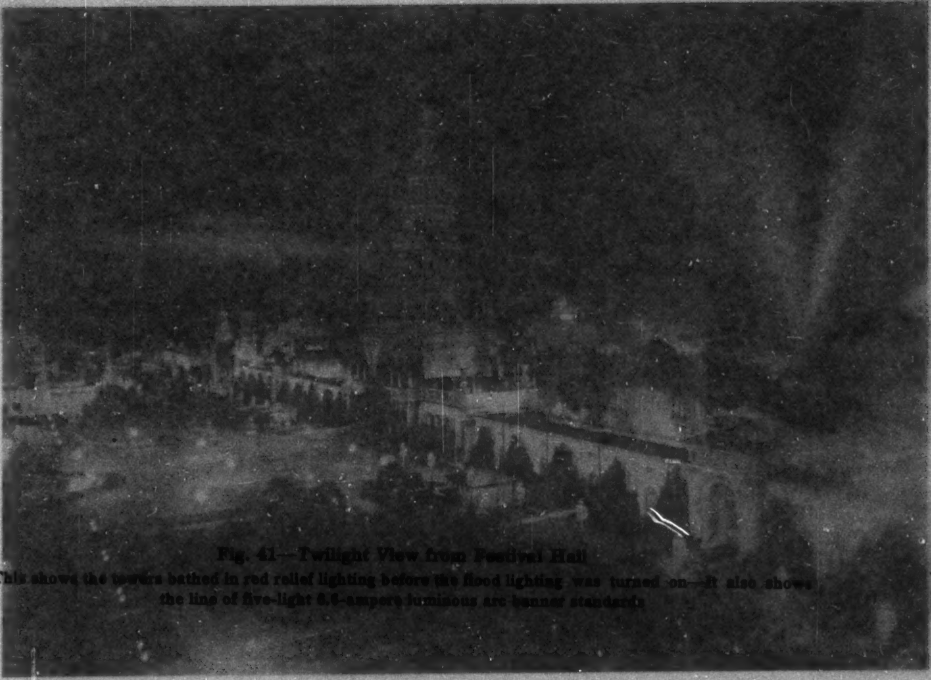


Fig. 41—Twilight View from Festival Hall

This shows the towers bathed in red relief lighting before the flood lighting was turned on—it also shows the line of five-light 6.6-ampere luminous arc banner standards

Vo
19

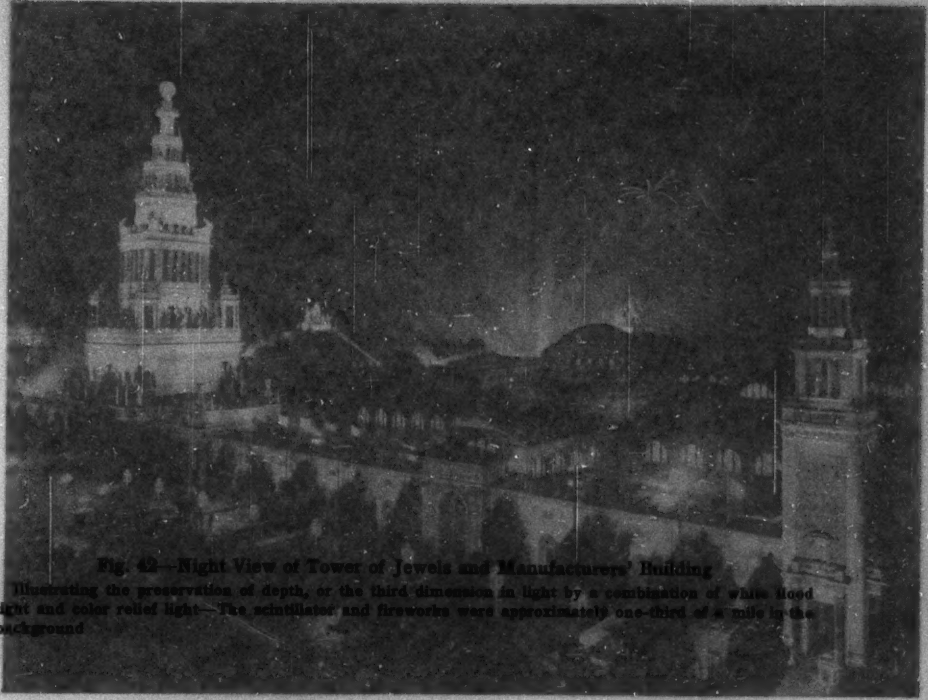


Fig. 42—Night View of Tower of Jewels and Manufacturers' Building

Illustrating the preservation of depth, or the third dimension in light by a combination of white flood light and color relief light—The scintillator and fireworks were approximately one-third of a mile in the background

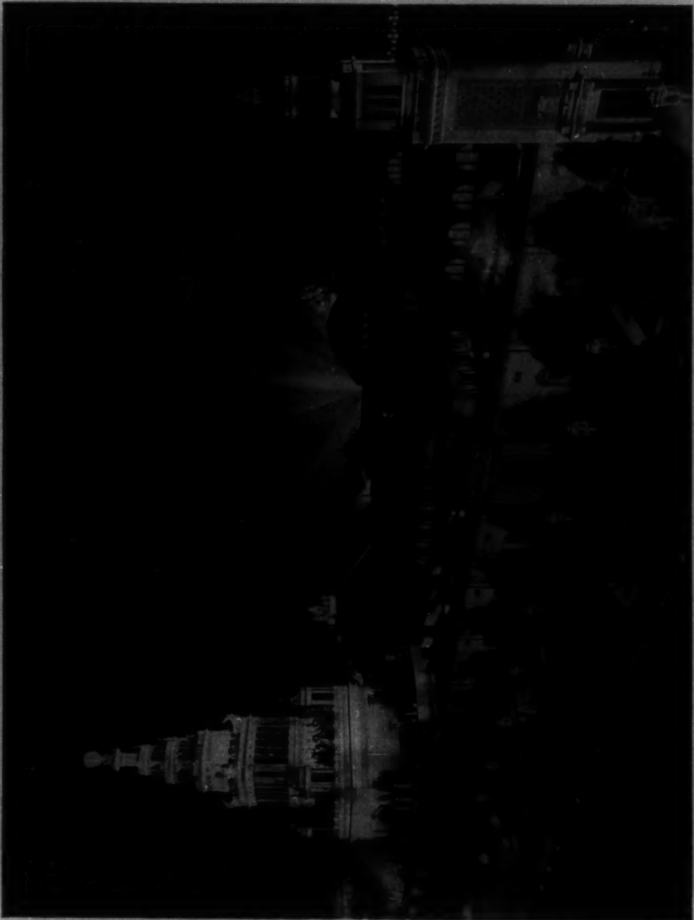


PLATE XXXI.
A. I. E. E.
VOL. XXXV, 1916.

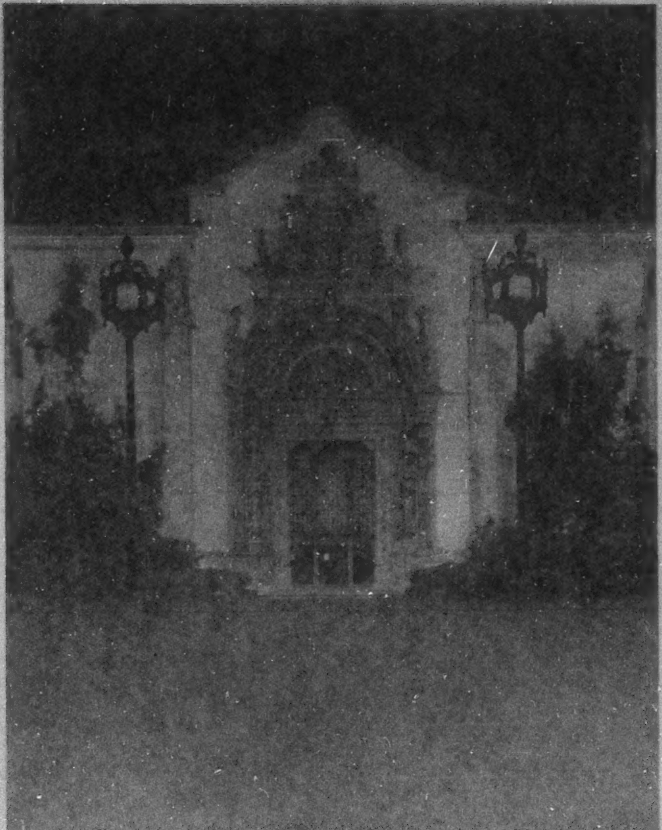


Fig. 43—South Portal—Palace of Industries
Showing three-light, 35-foot Cartouche standards—This illustrates excellent depth of detail with normal shadows

PLATE XXXI.
A. I. E. E.
VOL. XXXV, 1916.

Fig. 43—South Portal—Palace of Industries

Showing three-light, 35-foot Cartouche standards—This illustrates excellent depth of detail with normal shadows

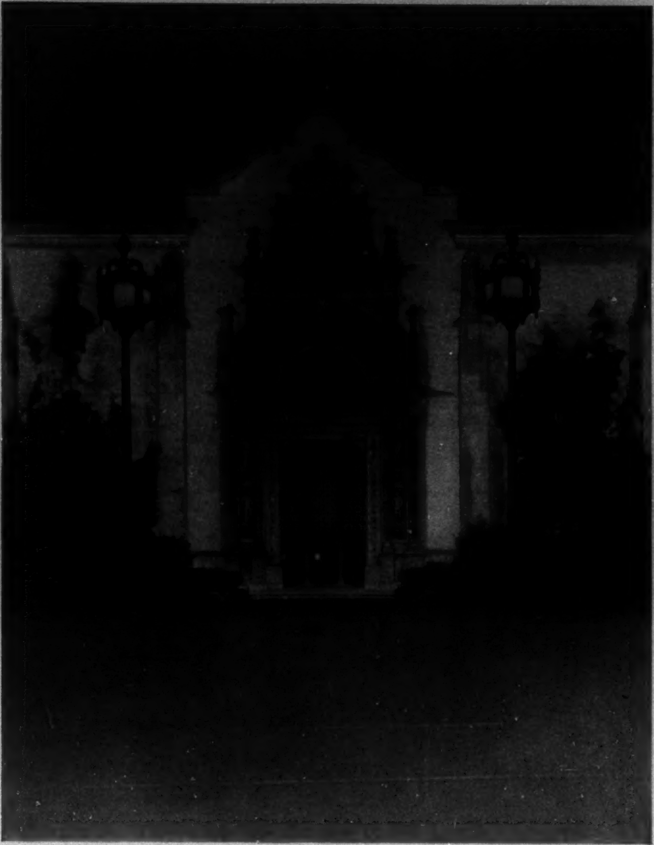


Fig. 44—Avenue of Progress from Zone Entrance

Showing the avenue flanked with three-light banner standards upon which were written the history of California and the Pacific—These in combination with the flags, which were lighted by individual arc projectors, were strongly suggestive of the carnival spirit—This made a very pleasing transition from the zone to the more artistic lighting of the main group of buildings

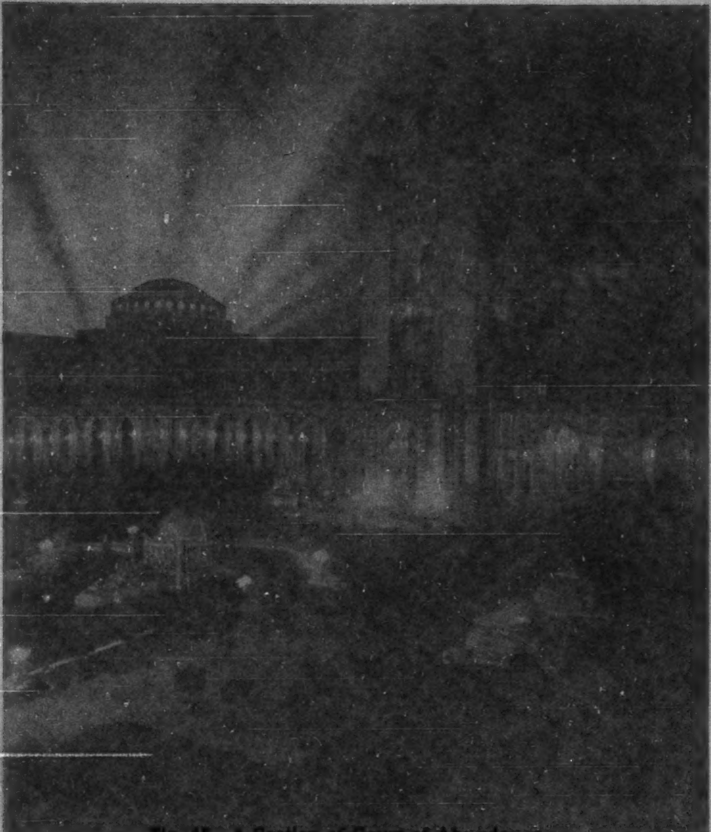
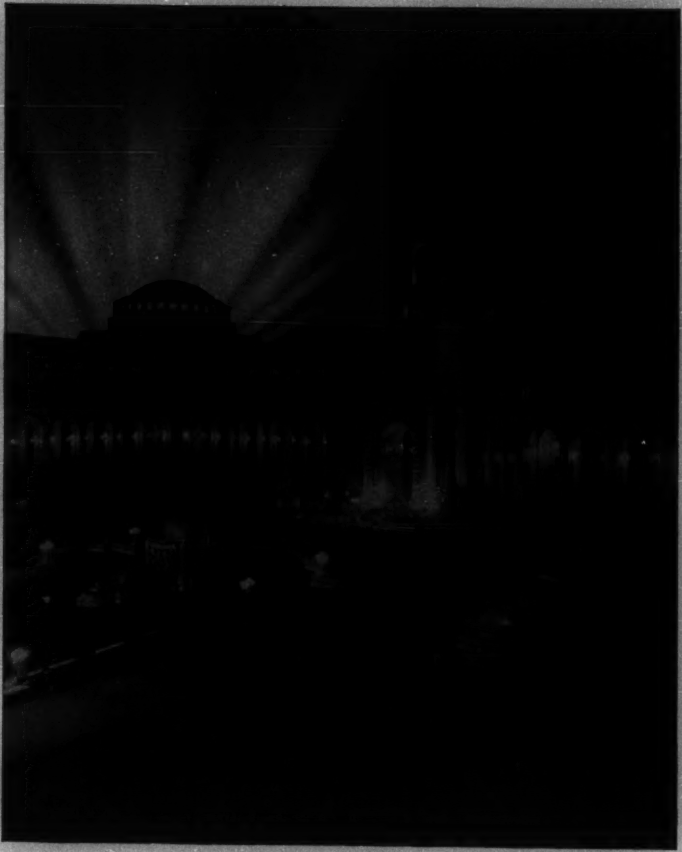


Fig. 45—A Section of Court of Abundance

Showing the organ tower and Aitken fountain, with steam caldrons and fiery serpent flambeaux—In addition to the happy effect of the orange colored cloister lanterns, the flaring gas and ruby steam caldrons and torches on the tower did much to heighten the feeling of mystery in this Court at night.



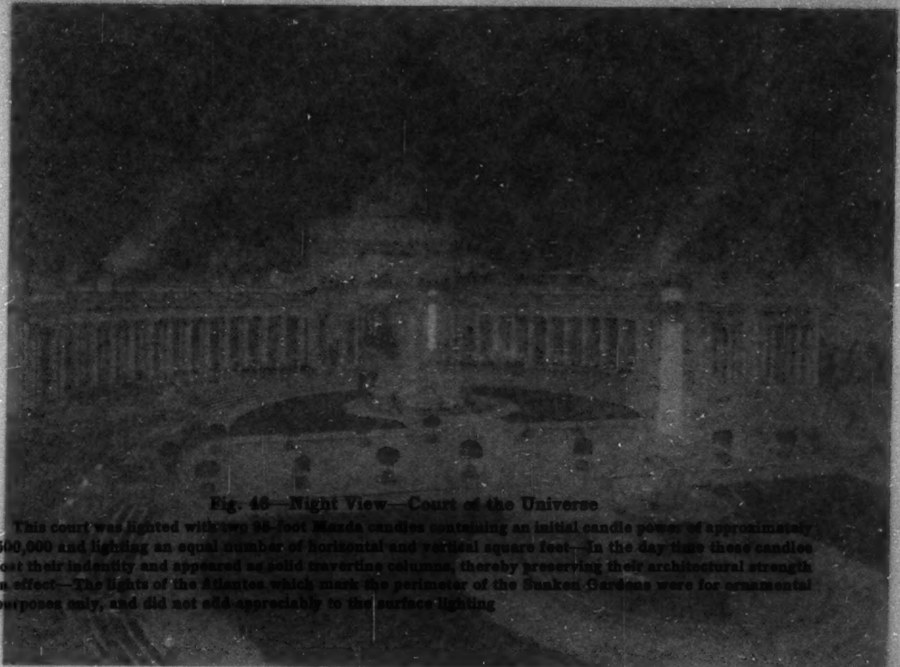


Fig. 46—Night View—Court of the Universe

This court was lighted with two 95-foot Mazda candles containing an initial candle power of approximately 500,000 and lighting an equal number of horizontal and vertical square feet—In the day time these candles lost their indentity and appeared as solid travertine columns, thereby preserving their architectural strength in effect—The lights of the Atlantes which mark the perimeter of the Sunken Gardens were for ornamental purposes only, and did not add appreciably to the surface lighting

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16

PAG

Fig. 47—North Approach to the Court of the Universe

Illustrating in silhouette the shell-type 1500-watt Mazda standards mounted on the balustrade for facade illumination—It also shows the seraphic jewel figures which were cross lighted each with individual incandescent searchlights placed behind the balustrades of the opposite facade—It will be observed that the flood lighting sources, as well as the lamps for illuminating the rear walls, were completely screened so that the architecture stands out free from interference of exposed sources

Vol. 3
1916

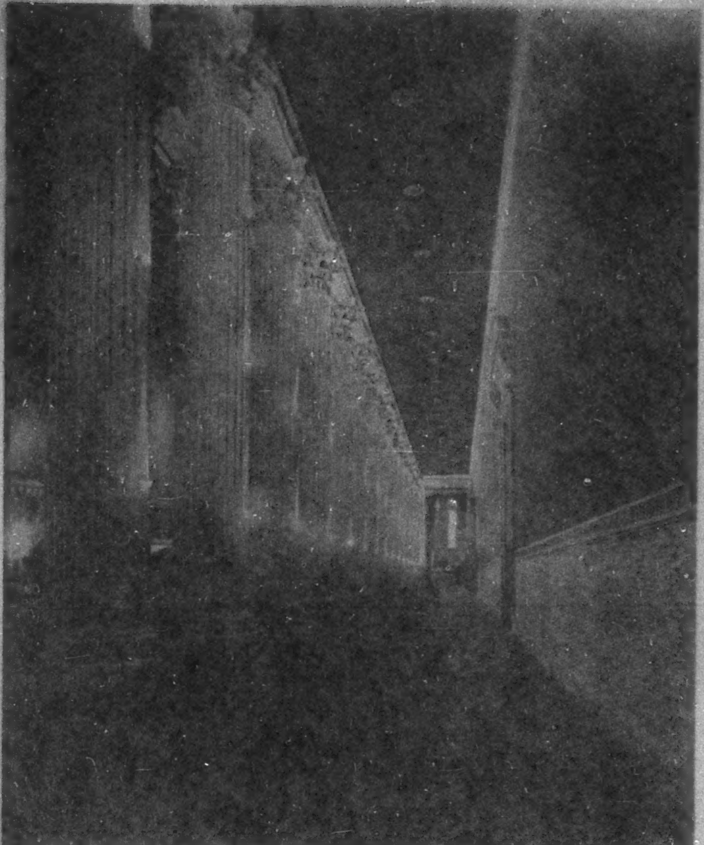
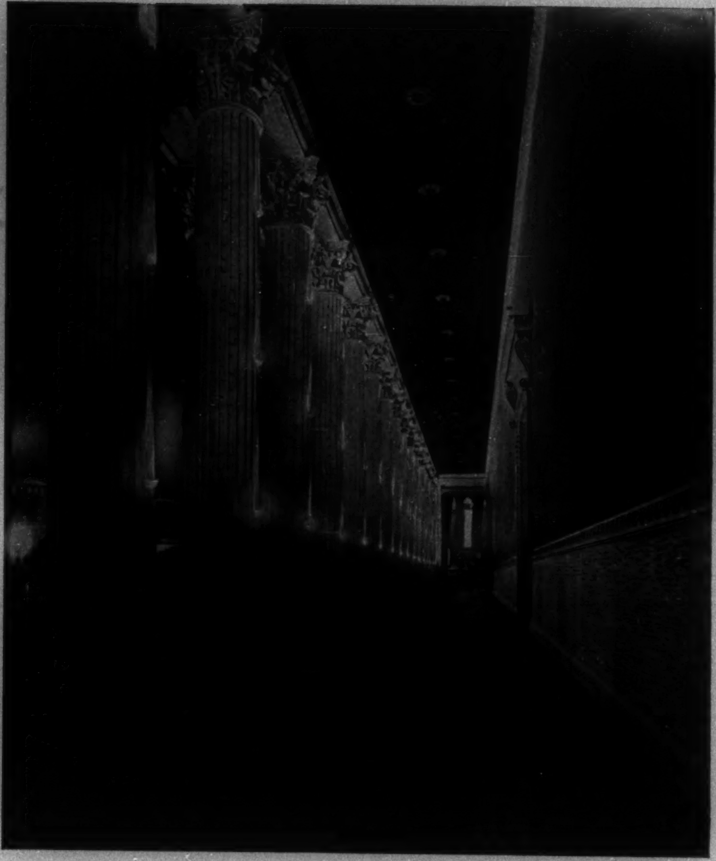


Fig. 48—Cusp Column Lights—Colonnade—Court of Universe

These lights were used for illuminating the walls and ceiling at the rear of the colonnade and they incidentally suggested a rain of fire—This method made it possible to obtain the illumination without having the source exposed to view at any position in the main court



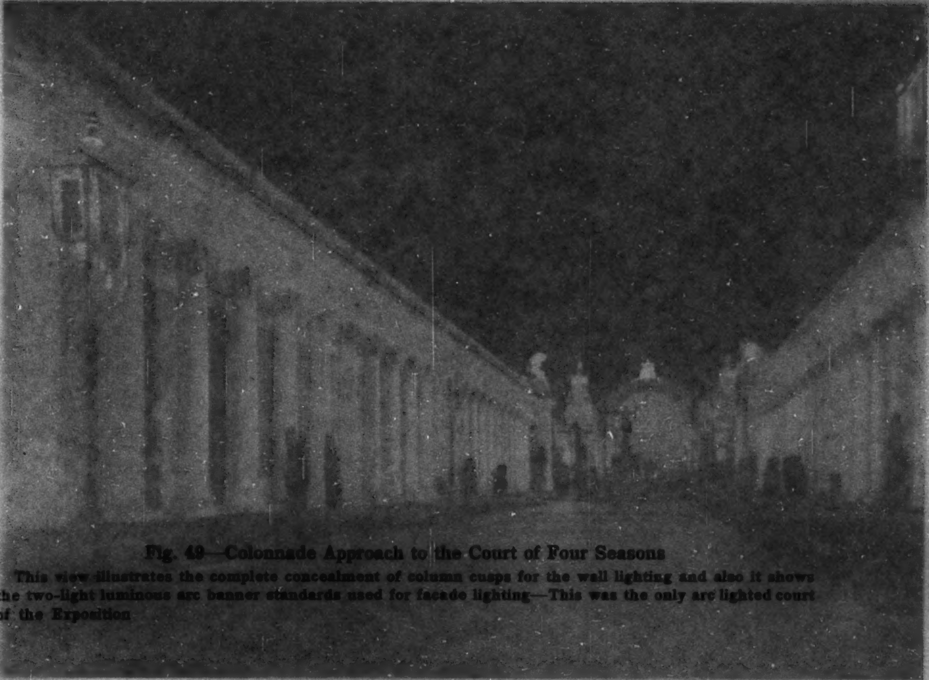


Fig. 49—Colonnade Approach to the Court of Four Seasons

This view illustrates the complete concealment of column cusps for the wall lighting and also it shows the two-light luminous arc banner standards used for facade lighting—This was the only arc lighted court of the Exposition

ol. 35
916

PAGE

PLATE XXXVIII.
A. I. E. E.
VOL. XXXV, 1916.

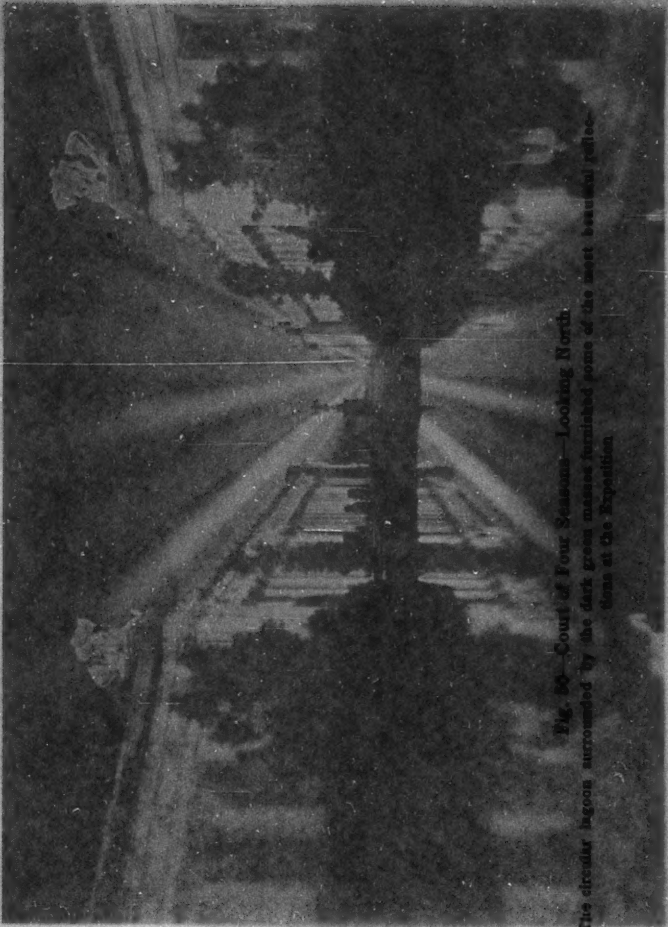


Fig. 50—Court of Four Seasons—Looking North

The circular lagoon surrounded by the dark green masses furnished some of the most beautiful reflections at the Exposition

Vol
191

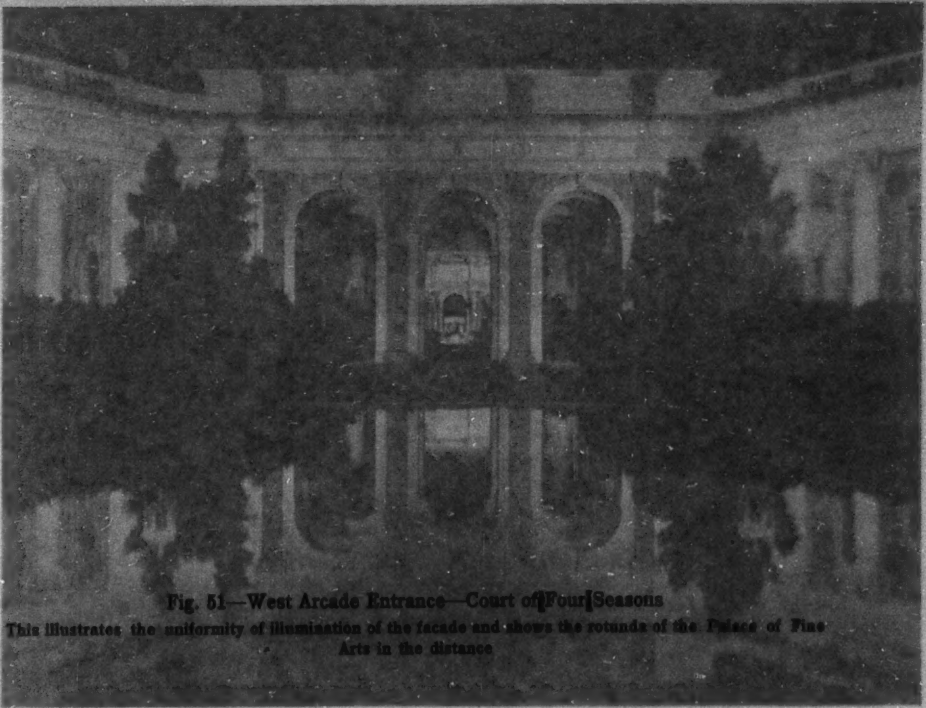


Fig. 51—West Arcade Entrance—Court of Four Seasons

This illustrates the uniformity of illumination of the facade and shows the rotunda of the Palace of Fine Arts in the distance

PLATE XL.
A. I. E. E.
VOL. XXXV, 1916.

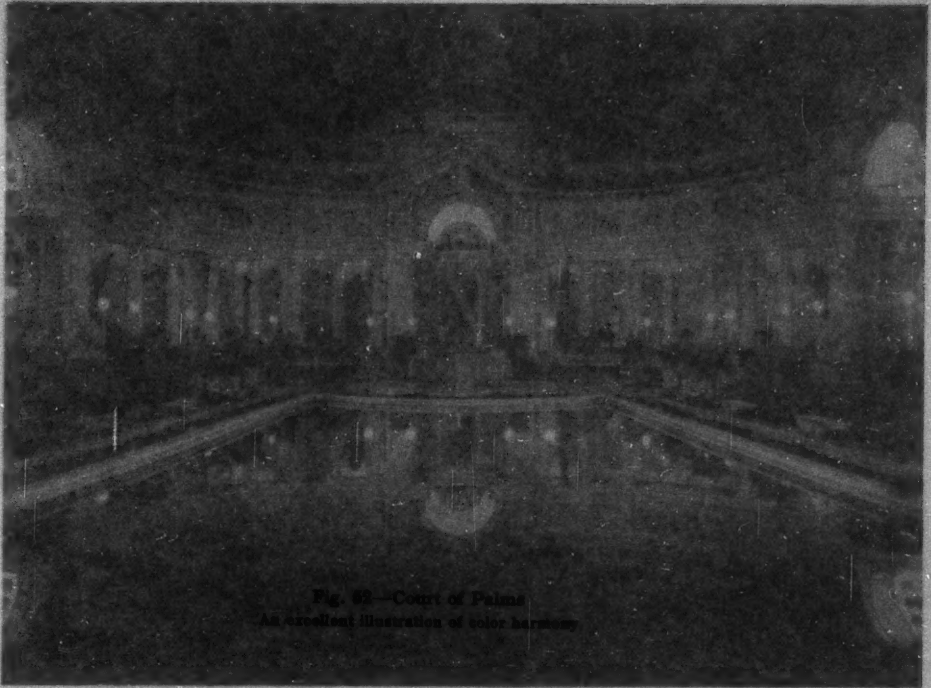


Fig. 62—Court of Palms
An excellent illustration of color harmony

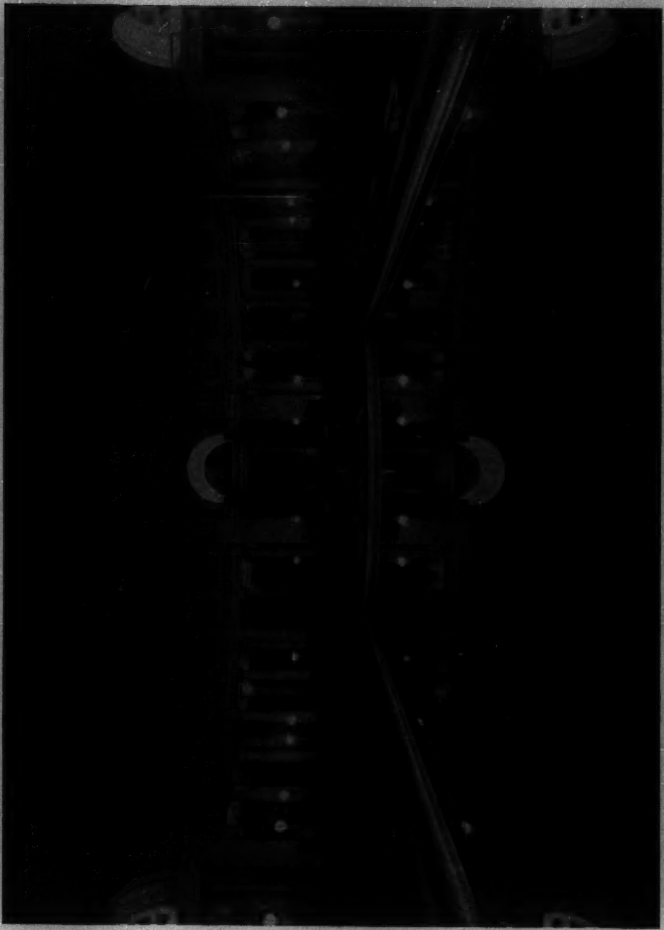


PLATE XLI.
A. I. E. E.
VOL. XXXV, 1916.

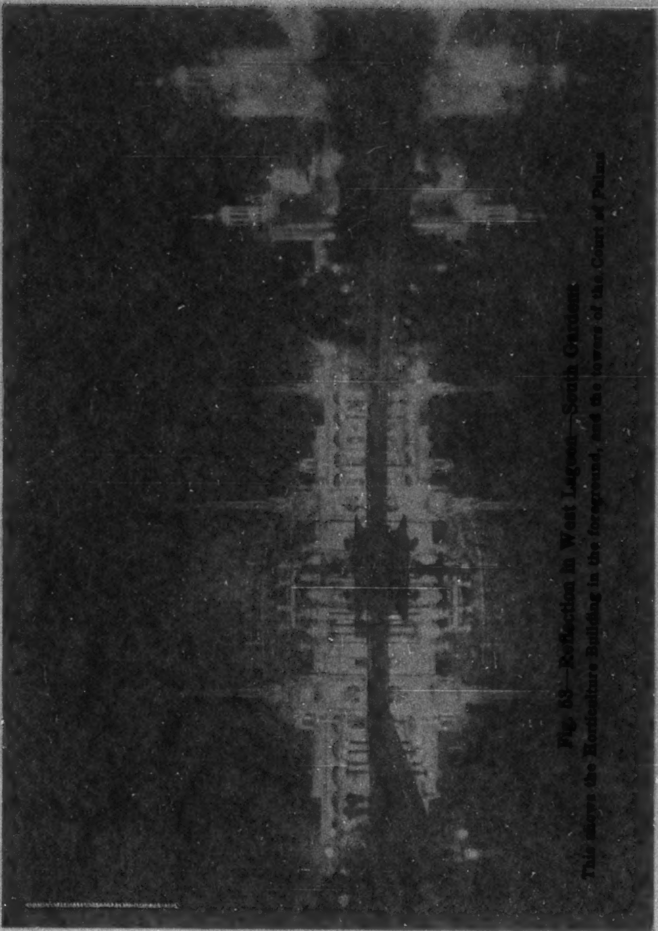


Fig. 53—Reflection in West Lagoon—South Gardens

This shows the Horticulture Building in the foreground, and the towers of the Court of Palms

PLATE XLI.
A. I. E. E.
VOL. XXXV, 1916.

Fig. 53—Reflection in West Lagoon—South Gardens

This shows the Horticulture Building in the foreground, and the towers of the Court of Palms

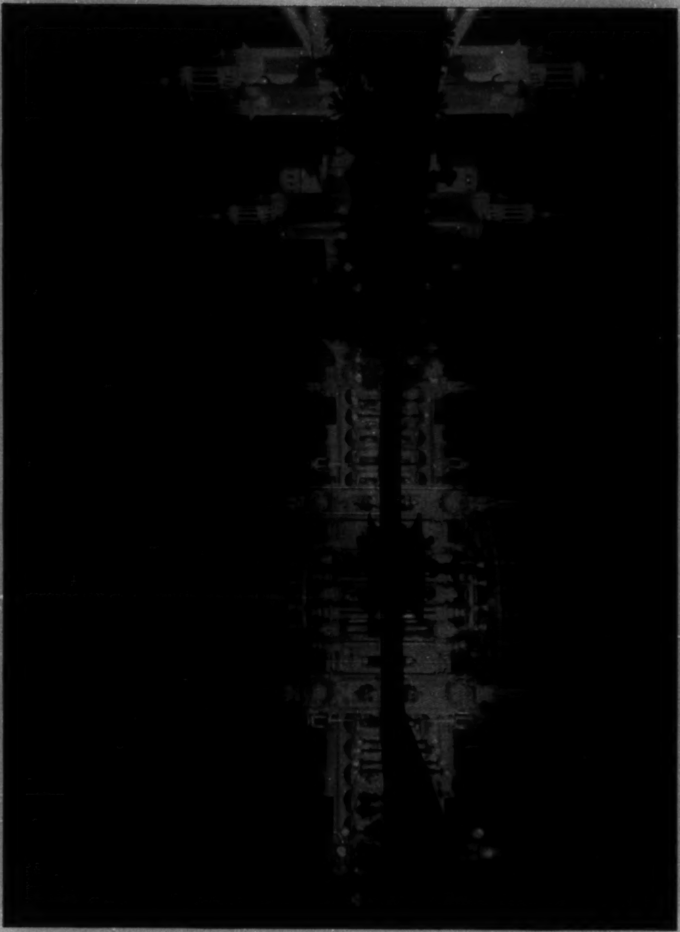


PLATE XLII.
A. I. E. E.
VOL. XXXV, 1916.

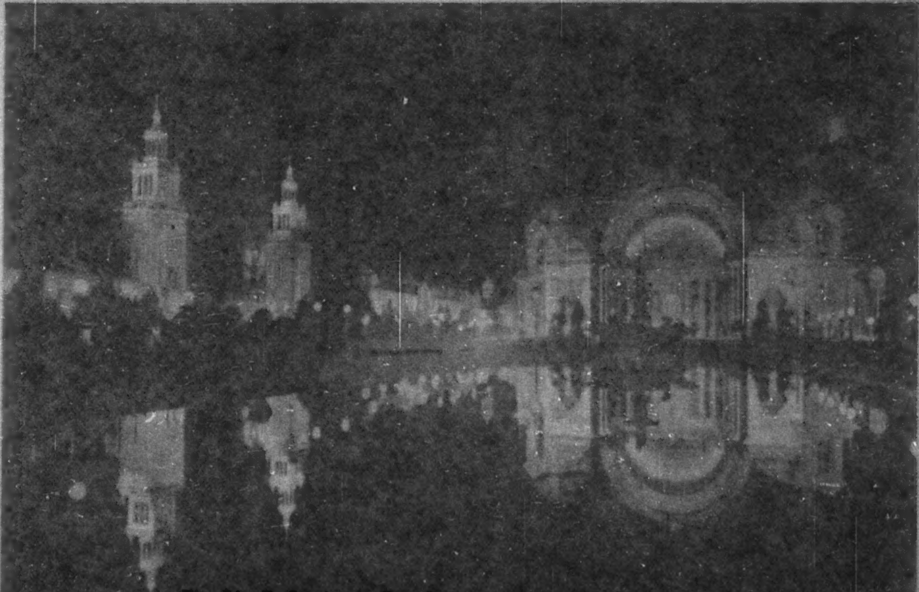


Fig. 54—Reflection in East Lagoon—South Gardens

Festival Hall on the right and the towers at the approach to the Court of Flowers at the left

Fig. 55—Tower of Jewels

This tower was 435 feet high and was decorated with 102,000 Novagem Jewels—the tower was flood lighted with search-lights and the shadows were illuminated with rose red light

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PAGE C

Fig. 56—West Facades of Palaces of Education and Food Products

Illuminated with 36-foot Cartouche standards, each containing three 6.6-ampere luminous arcs

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16

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191

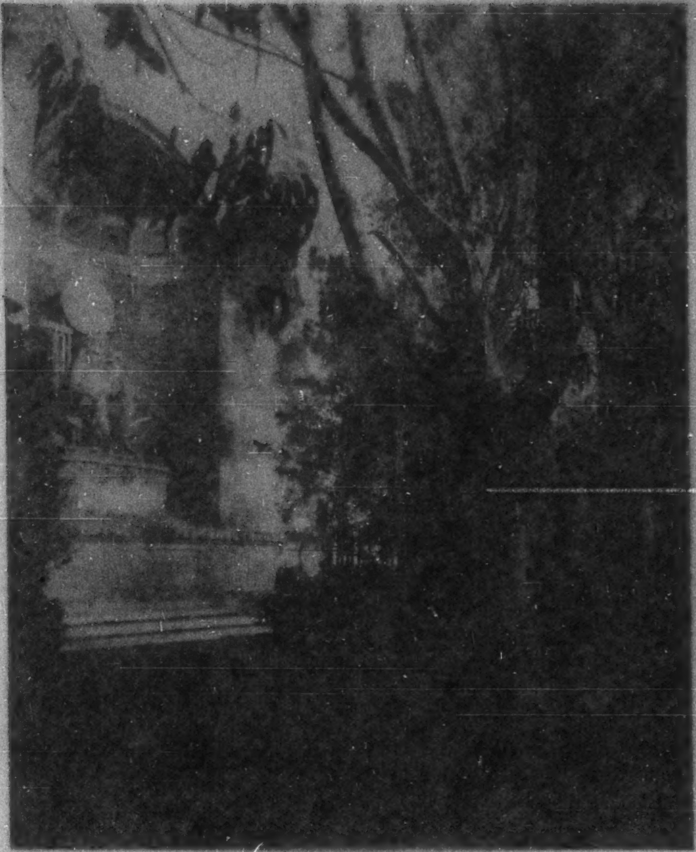
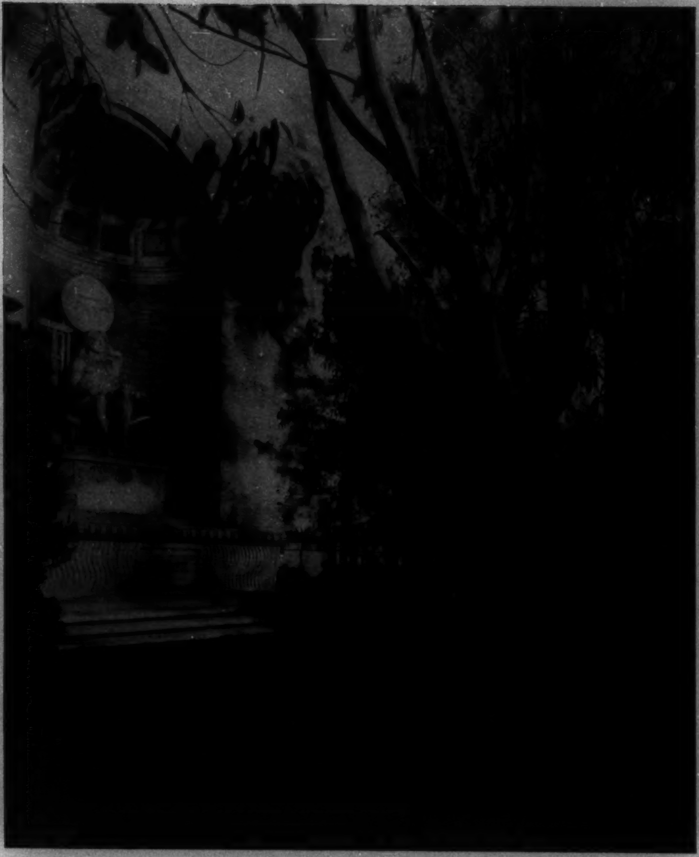


Fig. 57—Night View Under Trees—West Facade

A very striking illustration of light and shadow through the trees, and forming one of the most pleasing effects of the Exposition



Vo
19

Fig. 58—Palace of Fine Arts

Showing this illuminated by search lights from the roofs of the Palaces of Education and Food Products—The interior of the rotunda and the peristyle was illuminated with Mazda lamps placed in the soffits of the colonnade cornice—Three methods of illumination were thereby provided for; flood lighting, relief lighting and a combination of both—On certain nights color was also introduced in the searchlight beams

PLATE XLVII.
A. I. E. E.
VOL. XXXV, 1916.

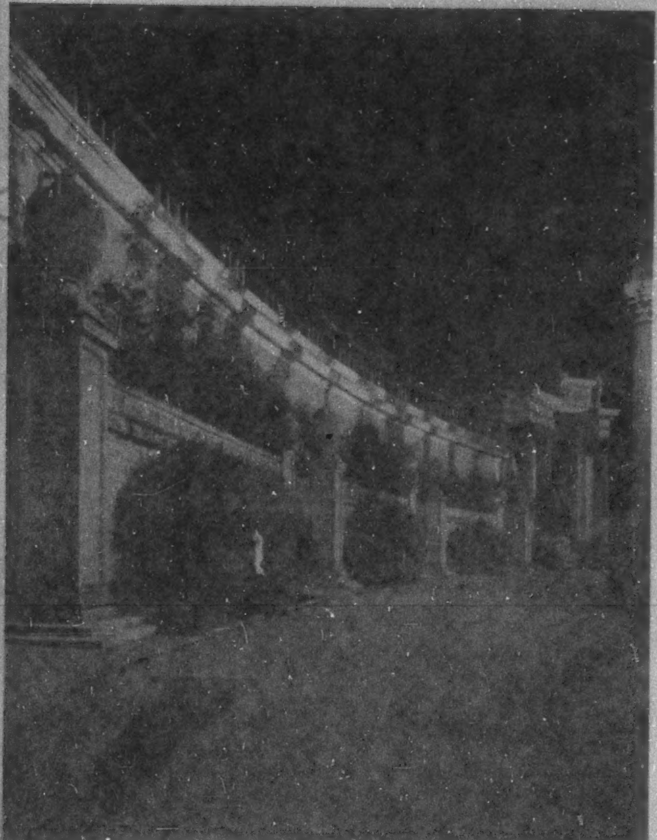


Fig 59—Peristyle Palace of Fine Arts—South Wing
A remarkable night picture

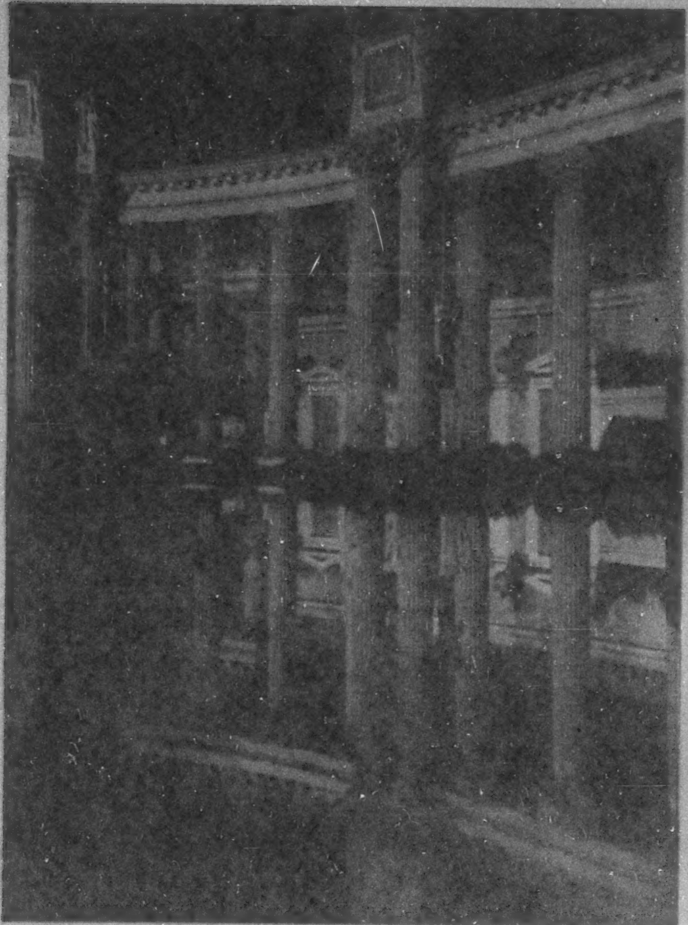


Fig. 60—Reflections of the Colonnade of the Palace of Fine Arts as Seen from the Rotunda

Vo
19

PLATE XLIX.
A. I. E. E.
VOL. XXXV, 1916.

Fig. 61—West Facade Palaces of Education and Food Products as Seen from the Palace of Fine Arts

This picture was taken on a night of high fog, which accounts for the overhead brilliancy produced by the diffused white light of the scintillator

PAGE G

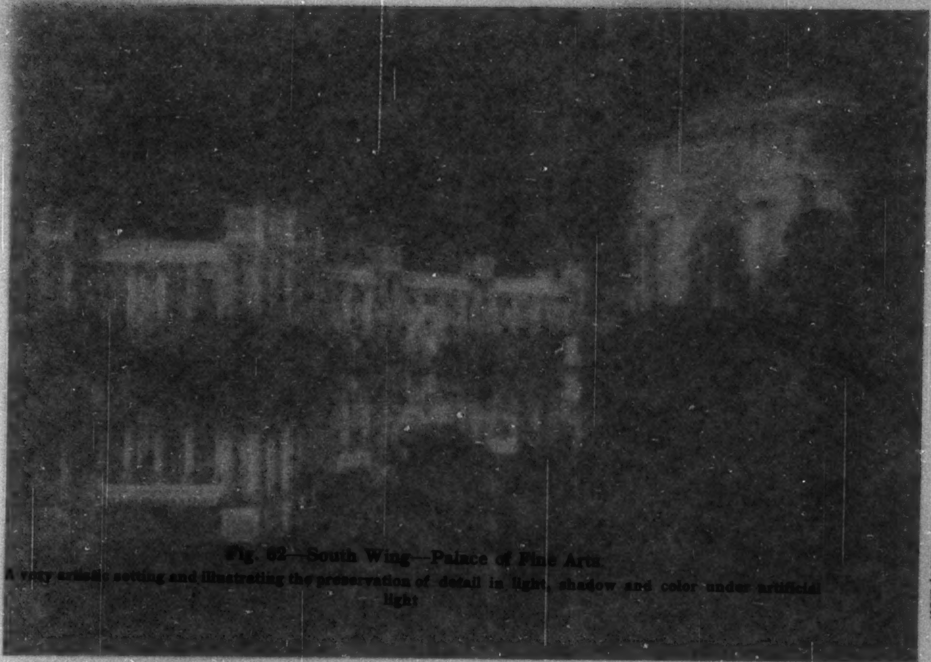


Fig. 62—South Wing—Palace of Fine Arts

A very artistic setting and illustrating the preservation of detail in light, shadow and color under artificial light

Vol. 35
1916

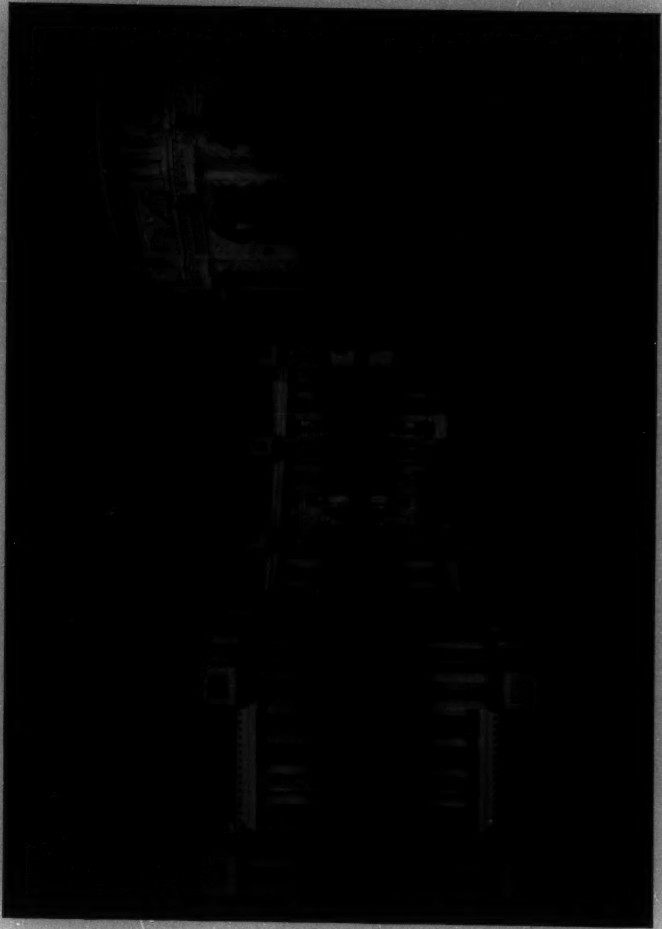
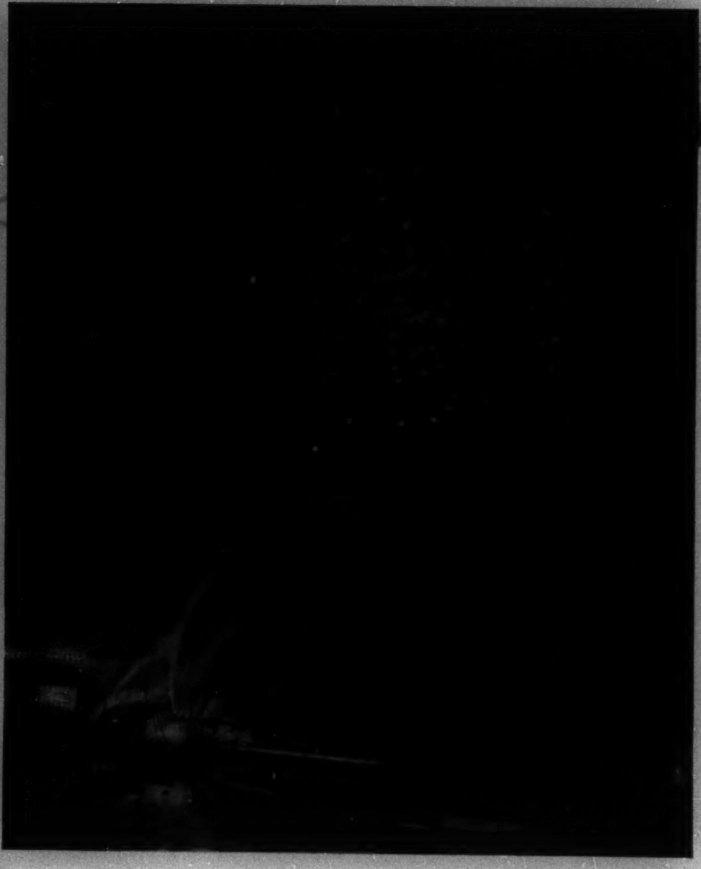


PLATE LI.
A. I. E. E.
VOL. XXXV, 1916.

Fig. 63—The Electric-Steam-Color-Scintillator
Taken at the time of the firing of the Zone salvo



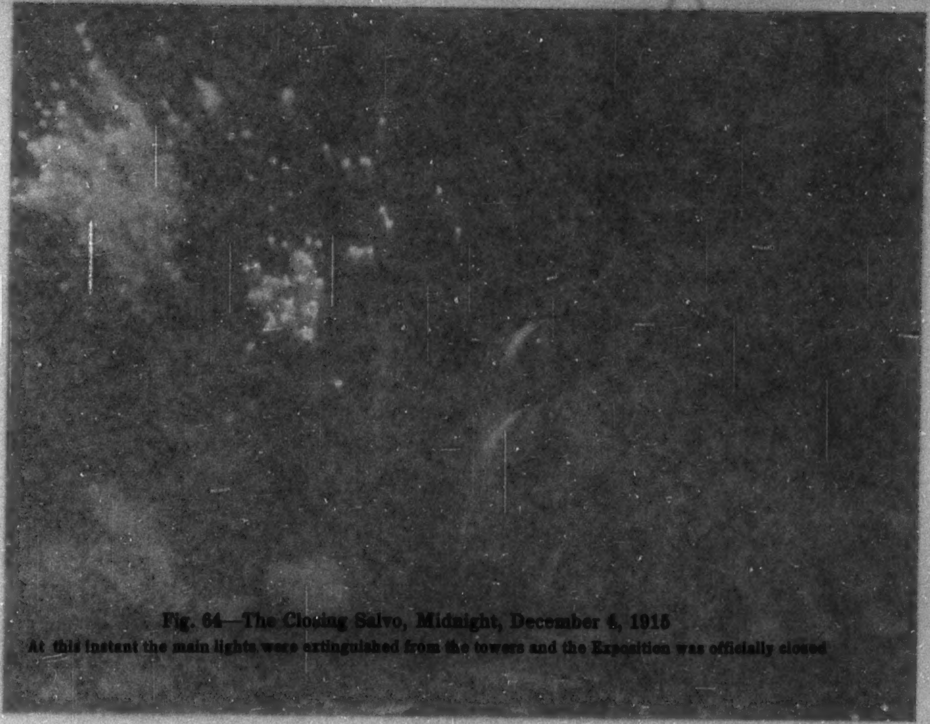


Fig. 64—The Closing Salvo, Midnight, December 4, 1915

At this instant the main lights were extinguished from the towers and the Exposition was officially closed

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 29, 1916.

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THE EFFECT OF HIGH CONTINUOUS VOLTAGES ON AIR, OIL, AND SOLID INSULATIONS

BY F. W. PEEK, JR.

Abstract of Paper

The dielectric strength of air, oil and solid insulations was determined for d-c. voltages up to 150 kv.

The d-c. visual corona voltage is practically equal to the maximum a-c. corona voltage for wires varying in radius from 0.013 cm. to the largest sizes. The variation of d-c. and a-c. corona voltages with air density is the same over a large range. The laws already given for a-c. voltages apply equally well for d-c. voltages in terms of maximum values.

The spark-over of gaps is the same on alternating current and direct current for equal maximum voltages when the gap is such that spark-over precedes corona. Thus, for the sphere gap the same laws apply for a-c. or d-c. voltages. This is true at various air densities.

When corona precedes spark-over there is generally a difference in a-c. and d-c. spark-over voltages. For a non-symmetrical gap, spark-over at normal air density takes place at the lowest voltage when the electrode surrounded by the denser field is (+). At low air densities spark-over takes place when the electrode surrounded by the denser field is (−).

Insulators spark-over at the lowest voltage when the cap, or electrode surrounded by the denser field, is (+). The (+) spark-over voltage generally corresponds closely to the maximum a-c. spark-over voltage.

The d-c. spark-over voltages in oil generally correspond closely to the maximum a-c. spark-over voltages. In wet oil the d-c. spark-over voltage is lower than the a-c.

The d-c. breakdown voltages of solid insulations, in good condition, are generally higher than the maximum a-c. voltages. This is especially so when the time of application is long and the insulation is thick. The d-c. breakdown voltage on insulations tested apparently increases directly with the thickness, while the a-c. breakdown voltage increases at a lesser rate. Laws are given.

When the insulation is moist, the d-c. and maximum a-c. breakdown voltages are generally approximately the same.

It appears that high-voltage direct current would be useful in certain high-voltage cable testing, etc.

HIGH CONTINUOUS or "direct-current" voltages were obtained from the 60 cycles alternating by means of a kenotron rectifier in combination with condensers and inductance coils.[1] A sketch of the connections used is given in Fig. 1.

---

[1] These tests were made with kenotrons loaned by Dr. Dushman of the Research Laboratory of the General Electric Company.

The condensers are charged up to the maximum of the alternating voltage wave. They remain at this voltage if there is no leakage, and no power is being taken at *A*. If current flows at *A* the condensers become partly discharged between the maximums of two waves and there is a double frequency ripple on top of the " d-c. " voltage across *A*. With a given current taken at *A* the amplitude of this ripple decreases with increasing condenser capacity and increasing inductance. With a given capacity and inductance the ripple decreases with decreasing current at *A*. With a given condenser and inductance the amplitude of the ripple decreases with increasing supply frequency.[2] The variation is less for connection 1*a* than 1*b*. Fig. 2 is an oscillogram of a wave taken with connection as shown in Fig. 1a and 0.05 amperes flowing—60-cycle supply. (This is many times the current flowing in the following tests.) Since in the following tests, the current flowing up to breakdown was practically negligible, there was no appreciable ripple on the voltage wave. Voltage was first measured with a static voltmeter, and by maximum of the wave on the voltmeter coil. When no power was taken the static voltmeter checked with the maximum of the alternating wave, and later, with sphere-gap measurements.

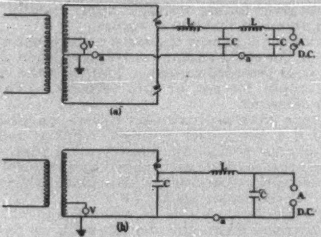

FIG. 1—CONDENSER CAPACITY = 0.064 MICROFARAD

AIR

Sphere Gaps. Sphere-gap curves were taken on 6.25- and 12.5-cm. spheres. The continuous, or d-c., voltage required to spark over a given gap was found to be $\sqrt{2}$ times the required

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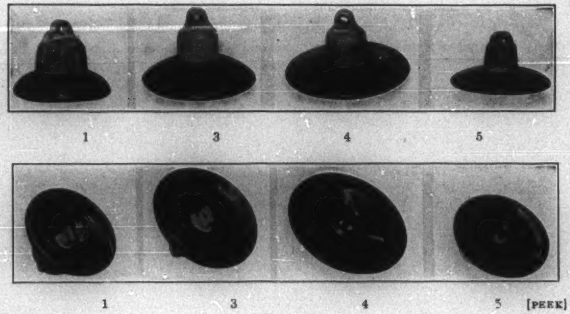
[2] See discussion by Dr. Hull, *G. E. Review*, March 1916.

The author wishes to acknowledge indebtedness to Mr. B. L. Stemmons for his skillful assistance in making experiments and calculations.

[PEEK]

FIG. 2—WAVE OF RECTIFIED VOLTAGE (25 KV., 0.05 AMPERE, 7-28-15).

Note: There was no appreciable ripple in voltages used in the tests. When the above oscillogram was taken a comparatively large current was allowed to flow in order to exaggerate the ripple.



[PEEK]

FIG. 9

effective sine wave alternating or a-c. voltage, that is, the d-c. spark-over voltage and the a-c. maximum voltage are equal. See Fig. 3. This is true for various air densities as shown in Fig. 4. The d-c. spark-over voltage curve of a sphere may, therefore, be calculated from the formula already given for a-c. voltages.[3]

$$e = g\,\frac{x}{f}$$

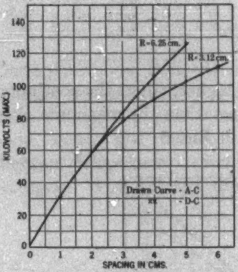


Fig. 3—A-C. and D-C. Spark-over Voltages for Spheres

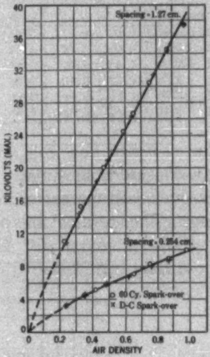


Fig. 4—Spark-over Voltages of 2.54 cm. Spheres at Various Air Densities

Where

$$g = 27.2\,\delta\left(1 + \frac{0.54}{\sqrt{\delta\,R}}\right)$$

x = spacing in cm.

$$\delta = \frac{3.92\,b}{273 + t} \qquad b = \text{barometric pressure in cm.} \quad t = \text{temperature, deg. cent.}$$

R = sphere radius in cm.

$$f = \phi\left(\frac{x}{R}\right) \qquad \text{(See reference below.)}$$

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[3] F. W. Peek, Jr., *The Sphere Gap as a Means of Measuring High Voltages.* Trans. A. I. E. E., Vol. XXXIII, 1914, p. 923.

This voltage may also be found by multiplying the a.c. effective voltages given by the standard curve by $\sqrt{2}$.

Needle Gaps. The d-c. needle gap spark-over voltage corresponds approximately to the maximum a-c. spark-over voltage over a considerable range. At the higher values the continuous spark-over voltage seems to be less than the maximum alternating. The results are plotted in Fig. 5.

TABLE I.
A-C. AND D-C. SPARK-OVER VOLTAGES OF 2/0 NEEDLES IN AIR.

Spacing, cm.	Kilovolts 60 cycle (max.)	Kilovolts d-c.
5.1	51.0	52.0
7.6	62.5	63.0
10.2	76.5	73.5
12.7	88.3	82.5
15.3	98.3	90.5

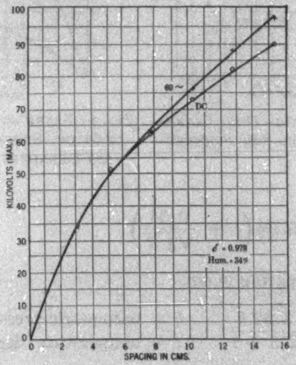

FIG. 5—SPARK-OVER OF 2/0 NEEDLES IN AIR

Corona. Visual corona and spark-over tests were made on concentric cylinders.[4] Typical data are given in Table II, and plotted in Fig. 6. In this test the outer cylinder was 3.81 cm. in radius. The polished inner cylinders or wires and tubes varied from 0.0038 cm. to 1.11 cm. radii.

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[4] See D-c. Corona Investigations of Watson, *Electrician*, London, 1909-1910, *Journal Inst. of Elec. Eng's*, June 1910. Also, Farwell, TRANS. A. I. E. E., Vol. XXXIII, 1914, p. 1631.

TABLE II.

D-C. AND A-C. VISUAL CORONA AND SPARK-OVER VOLTAGES

(CONCENTRIC CYLINDERS—NORMAL AIR DENSITY $\delta = 1$)

R radius outer cylinder cm.	r wire radius cm.	R/r	CORONA					SPARK-OVER		
			60 cycle calc. kv. (max)	D-c. + kv.	D-c. − kv.	A-c. $\mathcal{E}_{v\,max}$ kv./cm	D-c. $\mathcal{E}_v$ kv./cm	60 cy. kv. max.	D-c. + kv.	D-c. − kv.
3.81	0.0038	1000.0	4.9	6.4	6.4	186.0	244.0	..	Vibrates before sparkover	
3.81	0.0129	295.0	8.4	8.4	8.3	113.0	113.0	70.0		
3.81	0.0573	66.5	17.2	17.2	17.2	71.5	71.5	40.0	52.8	61.0
3.81	0.130	29.3	25.2	25.2	25.2	56.9	56.9	25.5	48.8	54.5
3.81	0.239	16.0	33.5	33.8	33.8	51.0	51.3	33.9	47.5	52.8
3.81	0.635	6.0	48.9	49.0	49.0	42.9	43.0	48.1	49.5	53.2
3.81	1.110	3.4	54.7	54.8	54.8	40.5	40.6	54.5	54.5	55.5

These data show that the maximum a-c. and the d-c. corona voltages are practically equal for wires over a large range of sizes. When the wire is positive the visual corona point is quite sharp and definite; when the wire is negative the slightest irregularity causes brush discharges at fairly low voltages. The percent difference between the positive and negative glow point cannot be great. Since this point is indefinite on the negative, the recorded value will depend to some extent on whether the observer considers the first brushes or the complete glow as the visual point. Even on apparently highly polished wires, when negative, the voltage for complete glow is generally several per cent higher than for local brushes.

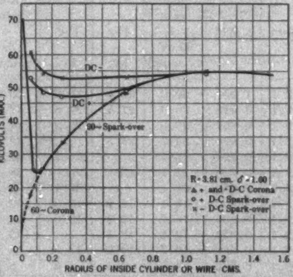

FIG. 6—A-C. AND D-C. CORONA AND SPARK-OVER FOR VARIOUS SIZES OF WIRE (CONCENTRIC CYLINDERS AT NORMAL AIR DENSITY).

The negative glow voltage will thus generally be read higher than the positive glow voltage. The spark-over voltages are equal when $\frac{R}{r} < \epsilon$ or where corona does not precede spark-over. Where corona precedes sparkover the d-c. voltage is higher than the a-c. The d-c. spark-over voltage is higher when the wire or conductor of the greatest field intensity is (—). This is shown in Fig. 6.

TABLE III.
D-C. AND A-C. VISUAL CORONA VOLTAGES
(CONCENTRIC CYLINDERS AT VARIOUS AIR DENSITIES)

R	r	R/r	δ	A-c. calc. 60 cy. kv(max.)	D-c. + kv.	D-c. − kv.	A-c. calc. g_v kv/cm. (max.)	D-c. g_v + kv/cm.	D-c. g_v − kv/cm.
2.90	0.0573	50.5	0.995	15.8	15.8	15.8	....	70.5	....
2.90	0.0573	50.5	0.838	14.2	14.2	14.2	....	63.2	....
2.90	0.0573	50.5	0.770	13.2	13.5	13.2	58.6	60.0	58.6
2.90	0.0573	50.5	0.720	12.6	12.7	12.4	56.0	56.5	55.2
2.90	0.0573	50.5	0.522	10.3	10.3	10.0	45.9	45.6	44.5
2.90	0.0573	50.5	0.363	7.9	8.1	7.8	35.1	36.0	34.7
2.90	0.0573	50.5	0.214	5.7	5.8	5.6	25.3	25.8	24.9

TABLE IV.
D-C. AND A-C. VISUAL CORONA VOLTAGES.
(CONCENTRIC CYLINDERS AT VARIOUS AIR DENSITIES.)

R radius outer cylinder cm.	r radius wire cm.	R/r	δ	A-c. calc. 60 cy. kv(max.)	D-c + kv.	D-c. − kv.	A-c. calc. g_v (max.)	D-c. g_v + kv/cm.	D-c. g_v − kv/cm.
2.90	0.239	12.1	1.00	30.0	30.0	30.0	50.5	50.5	50.5
2.90	0.239	12.1	0.915	28.0	27.8	27.8	47.0	46.8	46.8
2.90	0.239	12.1	0.857	26.3	..	26.2	44.2	....	44.0
2.90	0.239	12.1	0.824	25.7	25.5	..	43.3	42.9	..
2.90	0.239	12.1	0.797	25.1	..	25.1	42.2	....	42.2
2.90	0.239	12.1	0.720	23.1	23.1	..	38.8	38.8	....
2.90	0.239	12.1	0.680	22.1	..	22.1	37.1	37.1	....
2.90	0.239	12.1	0.550	19.1	19.2	19.3	32.1	32.2	32.4
2.90	0.239	12.1	0.435	15.7	15.7	16.0	26.4	26.4	26.9
2.90	0.239	12.1	0.357	13.5	13.5	..	22.7	22.7	....
2.90	0.239	12.1	0.260	10.7	10.9	11.6	18.0	18.4	19.5
2.90	0.239	12.1	0.082	4.8	4.4	4.6	8.07	7.4	7.75

Effect of Air Density on Corona and Spark-over of Wires. The visual corona and spark-over voltages were measured for concentric cylinders at various air densities. An outer cylinder of glass coated with the foil was used for these tests. The air was exhausted and the corona and spark-over voltages measured at different air pressures. The apparatus was the same as that used in a-c. tests and already described[5]. The results are given in Tables III, IV and V, and plotted in Figs. 7 and 8.

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[5] F. W. Peek, Jr., *Law of Corona*, A. I. E. E. TRANS., 1912, 1913.

The data in Tables III and IV show that the maximum a-c. and the d-c. visual corona voltages correspond down to $\delta = 0.3$. The difference is not great even at $\delta = 0.08$. The difference at the lower values of δ may be due to the difficulty in determining the exact starting point in these cases.

TABLE V.
D-C. AND A-C. SPARK-OVER VOLTAGES.
(CONCENTRIC CYLINDERS AT VARIOUS AIR DENSITIES.)

R radius outer cylinder cm.	r radius wire cm.	R/r	δ	60 cy. kv. max.	D-c. + kv.	D-c. − kv.
2.90	0.239	12.1	0.075	4.2	4.8	4.6
2.90	0.239	12.1	0.250	10.6	11.1	10.8
2.90	0.239	12.1	0.354	12.5	14.2	14.4
2.90	0.239	12.1	0.477	16.8	17.2	18.3
2.90	0.239	12.1	0.660	21.6	22.0	23.5
2.90	0.239	12.1	0.760	24.2	24.5	26.3
2.90	0.239	12.1	0.890	27.2	27.2	30.0
2.90	0.239	12.1	1.000	30.1	30.5	3.7

See corona data on this cylinder—Table IV.

Spark-over data are given in Table V for a 0.239-cm. wire. At the higher values of δ the positive spark-over voltage is lower than the negative and closely follows the maximum a-c. The positive seems to be slightly higher than the negative for very low values of δ.

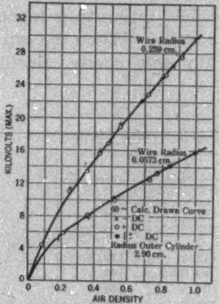

FIG. 7—VARIATION OF A-C. AND D-C. VISUAL CORONA VOLTAGES WITH AIR DENSITY

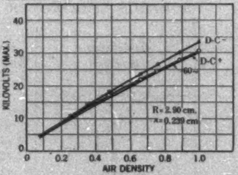

FIG. 8—D-C. SPARK-OVER OF CONCENTRIC CYLINDERS AT VARIOUS AIR DENSITIES

These tests show that the formula already given for a-c. corona may also be used for d-c. corona over a wide range of wire diameter, air density, etc.[6] The d-c. corona voltage is practically equal to the maximum a-c. corona voltage over a large range of conductor diameters.

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[6] F. W. Peek, Jr., *Law of Corona and Dielectric Strength of Air*. A. I. E. E. TRANS., 1911, 1912.

The d-c. visual corona voltage in kilovolts is

$$e_v = g_v r \log_\epsilon \frac{R}{r} \quad \text{wire in a cylinder}$$

$$e_v = 2 g_v r \log_\epsilon \frac{R}{r} \quad \text{parallel wires}$$

Where

$$g_v = g_0 \delta \left(1 + \frac{0.3}{\sqrt{\delta r}}\right) \text{ kv. per cm.}$$

where $g_0 = 31$ (concentric cylinders)

$g_0 = 30$ (parallel wires)

$$\delta = \frac{3.92\, b}{273 + t} \qquad b = \text{barometric pressure cm.} \quad t = \text{degrees centigrade.}$$

Surface Spark-over of Insulators. Spark-over tests were made on several standard insulators shown in Fig. 9. The results are given in Table VI. The spark-over voltage is highest when the cap or electrode around which the field intensity is highest is (−). This checks with the impulse tests.[7] When the cap is (+) the d-c. spark-over voltage generally very nearly coincides with the maximum a-c. spark-over.

TABLE VI.
SURFACE SPARK-OVER OF SUSPENSION INSULATORS.

Insulator number	60 cycle kv. (max.)	D-c. kv.	
		cap +	cap −
1	116.0	117.5	127.5
2	99.0	99.0	106.0
3	126.0	132.0	139.0
4	111.5	128.0	135.0
5	119.0	128.0	135.0

OIL

The "corona" and spark-over characteristics of oil are very similar to those of air. Practically the same laws are followed for a-c. voltages in both oil and air.[8] This apparently also holds for d-c.

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[7] F. W. Peek, Jr., *The Effect of Transient Voltages on Dielectrics.* A. I. E. E. TRANS., Vol. XXXIV, 1915.

Needle gap spark-over voltages for oil are given in Table VII

TABLE VII.
D-C. AND A.C SPARK-OVER TESTS ON 2/0 NEEDLES IN NO. 8 TRANSIL OIL AT 25 DEG. CENT.

Needle gap cm.	60 cycle kv. (max.)	D-c. kv. (max.)
0.317	21.2	21.7
0.635	34.7	33.5
1.27	50.5	50.2
1.91	65.0	66.0
2.54	86.5	82.5

and plotted in Fig. 10. The d-c. voltages correspond to the a-c maximum.

The effect of moisture on the strength of oil for a-c. and d-c voltages is given in Table VIII and Fig. 11.

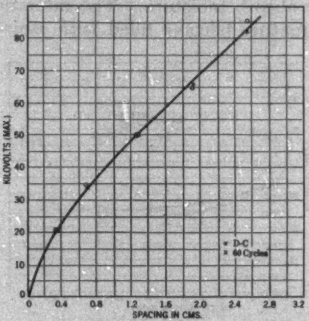

FIG. 10—A-C. AND D-C. SPARK-OVER VOLTAGES OF 2/0 NEEDLES IN NO. 8 TRANSIL OIL AT 25 DEG. CENT.

When the oil is wet the d-c. breakdown voltage is lower than the a-c. breakdown voltage. This is probably due to lining up of water particles under direct current.

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[8] F. W. Peek, Jr., *Law of Corona and Spark-over in Oil.* *G. E. Review*, August, 1915, also *Dielectric Phenomena in High-Voltage Engineering*. Chap. IV.

SOLID INSULATIONS

In air and in oil there is no appreciable loss until local breakdown occurs in the form of corona or brushes. In solid insulations loss starts as soon as voltage is applied and generally increases as the square of the voltage. The heating which results increases the loss and weakens the insulation. Practically all solid insulations absorb moisture. The interstices in the non-homogeneous structure become filled with moisture and gases. This makes, in effect, not only a complicated arrangement of resistances, but also of resistances and capacities in series throughout the material. Where the conducting paths extend through from terminal to terminal, either alternating or direct current can flow. But where the conducting paths extend partly through

TABLE VIII.

EFFECT OF MOISTURE ON THE DISRUPTION OF NO. 8 TRANSIL OIL AT 25 DEG. CENT.

(BETWEEN 1.27 CM. DIAMETER DISKS AT 0.5-CM. SPACING.)

Parts water added in 10,000	60 cycle kv. (max.)	D-c. kv.
0	62.3	61.5
0.5	33.5	34.7
1.0	33.4	34.3
2.0	31.7	30.2
5.0	27.3	24.7
10.0	25.4	23.0

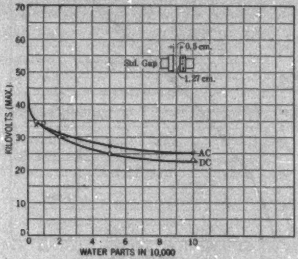

FIG. 11—EFFECT OF MOISTURE ON DISRUPTIVE STRENGTH OF NO. 8 TRANSIL OIL AT 25 DEG. CENT.

the structure they are, in effect, resistances in series with capacities; only alternating current can flow through these paths. The effective resistances as measured by alternating current and by direct current are quite different except in those solid insulations in which the "conducting" paths are arranged from terminal to terminal. The voltage distribution, heating, etc., will generally not be the same for a-c. and d-c. voltages. In the homogeneous materials, air and oil, d-c. breakdown voltages correspond to the maximum 60-cycle a-c. breakdown voltages. In most solid insulations relatively higher d-c. values should be

TABLE IX.

VARIATION OF 60-CYCLE PUNCTURE VOLTAGE WITH TIME OF APPLICATION ON VARNISHED CAMBRIC.

Tests Between 2.5-in. Plates, 1½-in. Radius Edge, in No. 6 Transil Oil.

Temperature deg. cent.	Sheets in.	Thickness mm.	kv. (max.)	Time sec.
25	1	0.30	24.8	2.3
		(12 mils)	21.3	12.0
			19.5	17.3
			17.7	41.5
			15.9	198.0
			14.2	900.0
100	1	0.30	14.5	2.0
			13.2	7.0
			12.6	11.0
			12.0	25.0
			10.8	620.0
			9.9	1400.0
25	2	0.60	29.8	213.0
			26.7	700.0
			25.6	1418.0
25	3	0.90	53.0	8.0
			45.2	51.5
			42.5	80.0
			41.7	138.0
			38.9	370.0
			37.1	905.0
25	4	1.20	69.3	4.0
			65.0	13.0
			64.3	15.0
			55.8	39.0
			53.0	80.0
			50.8	155.0
			47.3	580.0

expected, especially in insulations where the a-c. and d-c. "resistances" are decidedly different.

Varnished Cambric. Because of the effects of heating due to losses, voltage-time curves are necessary in order to compare the strengths of solid insulations. A-c. and d-c. voltage-time curves were taken on varnished cambric. The insulation under test was placed in transil oil between 5-cm. diameter brass plates with rounded edges. A given voltage was applied and time noted until breakdown occurred. The break-down voltages for various thicknesses of varnished cambric in the approximately

TABLE X.

VARIATION OF D-C. PUNCTURE VOLTAGE WITH TIME OF APPLICATION ON VARNISHED CAMBRIC.

Tests Between 2.5-in Plates, 1¼-in. Radius Edge, in No. 6 Transil Oil.

Temperature deg. cent.	Sheet in.	Thickness mm.	kv. (max.)	Time sec.
25	1	0.30	28.8	8.3
			27.2	20.0
			25.5	54.0
			23.8	94.0
			22.1	363.0
			20.4	668.0
			18.8	5400.0
100	1	0.30	21.0	1.5
			20.3	2.0
			19.6	38.0
			18.6	72.0
			17.0	600.0
			15.9	470.0
			15.2	1920.0
25	2	0.60	52.5	26.0
			50.0	50.0
			47.0	230.0
25	3	0.90	80.3	68.0
			77.5	130.0
			77.2	350.0
			75.5	1400.0
25	4	1.20	127.2	7.0
			120.0	16.0
			115.2	45.0
			110.0	100.0
			107.5	185.0
			105.0	330.0
			104.6	730.0

uniform field between parallel plates is given in Tables IX and X and plotted in Figs. 12 and 13.

Fig. 12 shows that the d-c. puncture voltage for a given thickness of cambric and for a given time of application is higher than the maximum a-c. puncture voltage. Fig. 13 shows that both the a-c. and d-c. puncture voltages decrease with increasing temperature. (The temperature referred to is that of the oil bath in which the insulation is immersed.)

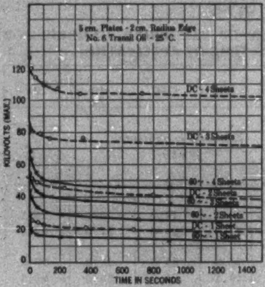

FIG. 12—VARIATION OF D-C. AND A-C. PUNCTURE VOLTAGES WITH TIME OF APPLICATION—VARNISHED CAMBRIC

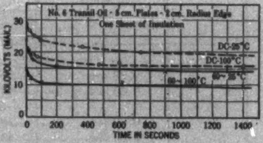

FIG. 13—EFFECT OF TEMPERATURE ON THE A-C. AND D-C. DISRUPTIVE STRENGTH OF VARNISHED CAMBRIC

The curves between puncture voltage and time are closely approximated by the equation[9]

$$e = e_0 \left(1 + \frac{a}{\sqrt[4]{T}}\right) \text{ kilovolts}$$

or the unit strength by

$$g = g_0 \left(1 + \frac{a}{\sqrt[4]{T}}\right) \text{ kv. per mm.}$$

Where

e = puncture voltage in time T, kilovolts (max.)
T = time in seconds.
e_0 = puncture voltage for $T = \infty$, kv. (max.)
g = breakdown gradient in time T, kv. per mm.
g_0 = breakdown gradient in $T = \infty$, kv. per mm.
a = constant depending upon the kind and thickness of the insulation and the frequency.

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[9] F. W. Peek, Jr., *Electrical Characteristics of Solid Insulation*, *G. E. Review*, November, 1915. Also Dielectric Phenomena in High-Voltage Engineering. Chap. VII.

This equation seems to hold well for a range of time between $T = 1$ and $T = \infty$. The breakdown voltage is plotted with $\frac{1}{\sqrt[4]{T}}$ in Fig. 14. The result is a straight line from which the above relation is obtained.

In Fig. 15 the a-c. and d-c. breakdown voltages of varnished cambric for the time, $T = \infty$, are plotted with thickness. As $T = \infty$, this is the highest voltage that the insulation will withstand indefinitely without puncture. For this material, at thicknesses from 0.3 mm. to 1.2 mm., the puncture voltage increases directly with the thickness, that is, the d-c. unit breakdown strength or gradient is constant. The unit strength of

TABLE XI.

A-C. AND D-C. PUNCTURE VOLTAGES OF VARNISHED CAMBRIC FOR VARIOUS THICKNESSES AND TIME OF APPLICATION

Time of application, seconds		∞	100	50	10	2
Sheets	Thickness mm.	Kilovolts to puncture (max.)				
1	0.30 a-c.	11.0	16.5	17.5	20.5	25.5
	0.30 d-c.	18.0	23.5	24.5	27.5	32.5
2	0.60 a-c.	20.0	31.0	33.0	39.0	47.0
	0.60 d-c.	43.0	49.5	51.0	55.5	62.5
3	0.90 a-c.	30.0	42.0	45.0	52.0	62.0
	0.90 d-c.	70.0	79.0	81.0	86.0	95.0
4	1.20 a-c.	37.0	52.0	55.0	64.0	78.0
	1.20 d-c.	96.0	111.0	114.0	123.0	137.0
Gradient kv. per mm. (max.)						
1	0.30 a-c.	36.6	55.0	58.5	68.5	85.0
	0.30 d-c.	60.0	75.0	82.0	92.0	108.0
2	0.60 a-c.	33.3	51.5	55.0	65.0	78.0
	0.60 d-c.	72.0	82.0	85.0	92.0	104.0
3	0.90 a-c.	33.3	46.5	50.0	57.9	69.0
	0.90 d-c.	77.5	87.5	90.0	95.5	105.0
4	1.20 a-c.	30.9	43.3	45.8	53.2	65.0
	1.20 d.c.	80 0	92 5	95.0	102.0	106.0

solid insulations under a-c. voltages decreases with increasing thickness. For a-c. voltages[10]

$$g = g_0 \left(1 + \frac{a}{\sqrt{t}}\right)$$

or

$$e = g_0 \, t \left(1 + \frac{a}{\sqrt{t}}\right)$$

For d-c. voltages apparently

$$g = g_0$$

$$e = g_0 t$$

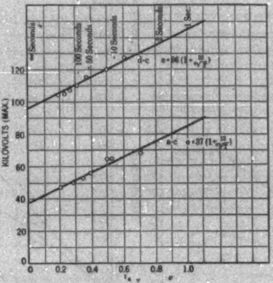

FIG. 14—VARIATION OF A-C. AND D-C. PUNCTURE VOLTAGES WITH TIME

4 sheets (1.20 mm.) Varnished cambric voltage plotted with $1/\sqrt[4]{T}$.

where

e = breakdown voltages of thickness t.
t = thickness in mm.
g = unit strength for thickness t, in kv. per mm.
g_0 = constant
a = constant depending upon the kind of insulation, time and frequency.

The curves in Fig. 16 correspond to those in Fig. 15 for T = 2 seconds.

It can be seen from the above relations that the ratio between the d-c. and a-c. puncture voltages for solid insulations cannot be constant but must increase with increasing thickness of insulation, especially where the time of application is long. This is shown graphically in the ratio curves in Figs. 15 and 16. Thus, in Fig. 16, where the time is two seconds, or relatively short, the d-c. puncture voltage very nearly corresponds to the a-c. maximum puncture voltage where the thickness is not great. In Fig. 15, where the time is a maximum, the d-c. puncture voltage is 2.5 times the a-c. maximum puncture voltage or 3.5 times the a-c. effective voltage for a thickness of 1.2 mm.

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[10] F. W. Peek, Jr., *Electrical Characteristics of Solid Insulation, G. E. Review,* November 1915. Also Dielectric Phenomena in High-Voltage Engineering.

Some of the d-c. puncture values (Tables X and XI) for single sheets of cambric apparently have a lower unit strength than a greater number of sheets. This is undoubtedly due to a greater probability of weak spots on a single sheet. Results of the same consistency cannot be expected or obtained on solid insulations as on gaseous and liquid insulations.

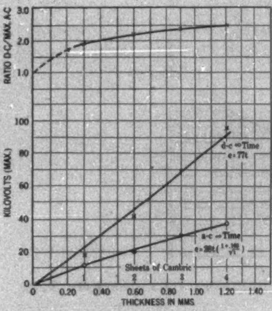

FIG. 15—VARIATION OF A-C. AND D-C. BREAKDOWN VOLTAGE WITH CONSTANT TIME

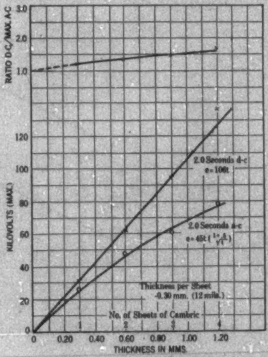

FIG. 16—VARIATION OF A-C. AND D-C. BREAKDOWN VOLTAGE WITH CONSTANT TIME

The thickness range of the insulation in the above tests was not great; it was limited by the available voltage (150 kv. direct current). It is *possible* that the d-c. unit strength will not remain approximately constant over a wide range.

Wet Insulations. Some 2.4-mm. (3/32-in.) treated pressboard was soaked in water and then partly dried out. A-c. and d-c. tests were made on this poor insulation. The results are given in Table XII.

5 kv. was thrown on the insulation, after the first minute the voltage was increased to 7.5, then to 10, etc., until breakdown occurred. If breakdown occurred before the end of the minute the time was recorded in seconds. For example, in the first a-c. test, insulation No. 6 withstood the voltage for 60 seconds at 5.0 kv., 60 seconds at 7.5 kv. and 5 seconds at 10 kv. when breakdown occurred. It will be noted that the d-c. and a-c. maximum breakdown voltages average about the same in this insulation, which was conducting from terminal to terminal. In some of the tests, in fact, breakdown takes place at a lower voltage on direct current than alternating current. This is, perhaps, due to a better lining up of moisture by direct current. Some of this insulation, dry and in perfectly good condition, was then tested in the same way. Starting at 5 kv. the voltage was increased every 60 seconds in 2.5-kv. steps until breakdown occurred; breakdown resulted on alternating-current when 70 kv. (max.) was reached; on direct-current when 130 kv. was reached.

TABLE XII.

A-C. AND D-C. TESTS ON WET INSULATIONS

0.24-cm (3/32-in.) Vacuum Treated Pressboard.

(Soaked in water and partly dried.)

Ins. test no.	Megohms res.		Kilovolts max.) 5.0	7.5	10.0	12.5	15.0	17.5	20.0	225
TIME (Figures show time in seconds at various voltages.)										
6	(120)	a-c.	60	60	5					
			60	60	50					
		d-c.	60	60	12					
			60	60	20					
9	(300 - 1500)	a-c.	60	60	60	60	2			
			60	60	60	17				
		d-c.	60	60	40					
			60	60	38					
4	(1000 – α)	a-c.	60	60	50					
			60	60	50					
		d-c.	60	60	60	60	17			
			60	60	30					
5	(2000 +)	a-c.	60	60	60	60	60	60	60	10
			60	60	60	60	60	60	30	
		d-c.	60	60	60	60	60	0		
			60	60	60	60	0			

Similar tests were made on sections of paper-insulated cables that had absorbed varying amounts of moisture. In those sections in the worst condition as indicated by low puncture voltages, the d-c. and a-c. maximum puncture voltages averaged about the same. In the sections in the best condition the d-c. puncture voltage was somewhat higher than the maximum a-c. voltage.

There is considerable difficulty in practise in making a-c. voltage tests on long lengths of cables, due to the size of the apparatus, which is necessarily large on account of charging current. The necessary kilovolt-amperes often amount to several hundred. The wave shape is often distorted by the leading current, the apparatus is difficult to move about etc. D-c. tests would eliminate these difficulties, as very small apparatus would be required, providing such tests would detect faulty sections, etc. It cannot be said that a given d-c. voltage is equivalent to a given a-c. voltage. The above tests indicate, however, that faulty sections of cable could be as equally well located by d-c. tests as by a-c. tests. In cases of cracks, etc. the air- or compound-filled space would be broken down at the same maximum voltage on direct current or alternating current. In case of a fault due to moisture the breakdown would apparently take place at about the some voltage, alternating current or direct current. In the case of a cable in good condition there would be much less likelihood of injury by direct current than by alternating current of the same maximum voltage. A d-c. voltage equal to the maximum of the a-c. test voltage would, therefore, seem suitable for such tests.

DISCUSSION ON "THE EFFECT OF HIGH CONTINUOUS VOLTAGES ON AIR, OIL AND SOLID INSULATIONS" (PEEK), CLEVELAND, OHIO, JUNE 29, 1916.

John B. Whitehead: We have again to acknowledge our debt to Mr. Peek for a most valuable contribution to our knowledge of the electric strength of air, and now also that of liquid and solid insulation.

Referring to Mr. Peek's observations on the comparison of alternating and continuous voltage at which corona appears, I have recently been conducting, in conjunction with Mr. W. S. Brown, a series of similar experiments. The results of these experiments show some variation from those obtained by Mr. Peek.

The expressions for the critical corona voltage in terms of the diameter of the conductor, as given by Mr. Peek and as given in my several papers on "The Electric Strength of Air," differ somewhat but not widely. Experiments by Farwell and others on corona forming continuous potentials differ as between positive and negative potentials, and reveal some question as to whether there is any agreement between alternating and continuous corona potentials. In view of these differences our experiments have aimed to take alternating and continuous observations on the same apparatus, under the same conditions and with the electroscope and such other precautions as to measurement as would insure accurate results. The method used for obtaining d-c. potential is the same as that shown by Mr. Peek in the lower half of Fig. 1. That is, we have used a kenotron with one side of the circuit grounded. Our experiments have differed, however, in the method of measuring the continuous voltage. For this we have used a standard d-c. Weston voltmeter, with series-connected, non-inductive resistance aggregating a million and a half ohms. Mr. Peek, apparently has depended on the ratio of transformation of his high-tension transformer as an indication of his d-c. voltage. For our alternating voltages we have used the ratio of transformation of the transformer together with careful oscillograms on the low-tension side for determining the maximum values.

Our results show a marked difference between positive and negative corona voltages for a range of wires between 0.07 and 0.23 cm. diameter. When the wire is negative the corona forming voltage within this range varies from 6 per cent to about 2½ per cent higher than positive. Mr. Peek states, as shown by Table II that within the corresponding range and indeed throughout the entire range of his observations, there is no difference between positive and negative corona forming voltage.

Mr. Peek, as usual, has contributed a most interesting paper. In my opinion the value of it would be greatly enhanced if it contained a better description as to the conditions of accuracy under which the observations were taken. For example, a static voltmeter seems to have been relied on for the continuous voltage measurements. My experience with this type of instrument leads me to feel that it is far from accurate. One would also like to know the general conditions under which the maximum value of the alternating voltage was determined on the low voltage side and how often throughout the range of voltage used. No statement is made as to how closely any of the observations may be repeated. In connection with the puncture tests on solid insulation it would be particularly interesting if Mr. Peek has been able to secure uniform results with repeated observations of the puncture tests on single sheets of material.

One must always envy the exceptional facilities which Mr. Peek is able to bring to bear on his experimental problems. A uniform source of continuous potential up to 150 kv. offers promise of many valuable observations.

William Baum: Whenever the subject of high continuous voltages has come up in the past in the engineering societies it was admitted with regret that we had no definite data on d-c. corona and puncture voltages. We know now with certainty that the d-c. puncture voltage is 2.5 times the a-c. maximum puncture voltage, or 3.5 times the a-c. effective voltages for an insulation thickness of 1.2 mm. where the time of test is a maximum.

This brings back to my mind the old claim of Mr. Thury and his followers that an effective alternating pressure of 10,000 volts imposes on insulation a stress of the same order of magnitude as a d-c. pressure of 25,000 volts.

It appears now that Mr. Thury was right when he claimed that d-c. cables require less insulation than a-c. cables designed for the same voltage, so that if d-c. voltage has advantage of lower disruptive effects, as Mr. Peek has shown for normal operating conditions, this would make the application of high-tension d-c. current for transmission purposes more favorable. Indeed the Thury system, although it has met with some criticism in this country, has further advantages which, I believe, have never been pointed out sufficiently until the present time.

Without wanting to go into the details of the high-tension d-c. system for transmission, I take this opportunity of calling attention to the multi-circuit feature which makes a constant d-c. system especially efficient for inter-connecting a number of stations, systems or net-works for the transfer of power. One of the most important applications would be that to long distance railroading, as transcontinental lines, by inter-connecting by such a series system the substations of the railroad, and all available sources of power near the railroad.

Mr. Peek has suggested the testing of cables by direct current, and I agree with him that faults in cables installed could be found just as easy or easier with direct current than with alternating current. Anybody who has had to do with cable testing in installations appreciates the independence of the source of electric power which would exist if we could make use of the kenotron rectifier described in the paper in connection with a small transportable gasoline-electric set, or similar high-tension direct-current rectifiers which have been in use abroad for a number of years, and which are known as the Geoffroy & Delore and Delon apparatus. In fact, the Siemens-Schuckert works have made puncture tests with their Delon rectifier which check very close with Mr. Peek's own exhaustive and defined experiments.

I believe that Mr. Peek should continue his investigations and extend them over long lines of cables which have been installed, so that no doubt may arise in the minds of those who question the applicability of high-tension direct current; for testing purposes and transmission systems.

Stanley Farwell: I can remember when I was working on corona that I went to Mr. Peek's papers and Dr. Whitehead's papers and used them more or less as text-books. My work has been entirely with direct-current corona, and on that account I am unable to make any comparison between that and the alternating-current corona. In my work it did seem to me that the d-c. corona lends itself better, perhaps, to the study of the physical nature of corona than does the alternating current.

In the work I did, I started out to do certain definite things, but I found as I went along, the things I started to do got further and further from me, because I ran into so many new things that apparently had not been explained. I went to one of the best physicists I knew and got him to try to help me out on the physical explanation of the formulas such as are given in Mr. Peek's papers and Dr. Whitehead's papers and my own. I found, after a while, that we got up against a stone wall.

At the University of Illinois, they are now working on some further experiments, and are taking different gases, trying to study them, and get some knowledge of the physical laws underlying corona. I used air entirely, and I found that when working with parallel cylinders, the change in the composition of the air, due to corona, seemed to cut quite a figure. We are now trying to get away from that by using simple gases.

C. E. Skinner: All of us who have had to do with insulation and insulation testing have many times wished we had available direct current so that we could get away from some of the complications which constantly beset us in the testing of insulation with alternating current. We have variables enough without the extras that come in due to the variations from frequency, wave form and things of that kind. Insulations are about the most difficult things to investigate, because of the fact that there are such an enormous number of variables coming in to mask results.

Our own work has been more along the line of the measuring of the losses at high voltages. The condition we have to meet in practise is that we have stresses due to alternating current and some of the important features in connection with this phenomenon are in connection with losses which occur in the insulating material.

For some time I have had some experiments going on with a view to seeing if we could not determine beforehand when insulation was in condition to break down, before it actually broke down. All of our early work was based on breakdown values after the breakdown occurred, and I am very pleased to see that some recent work indicates the possibility of predicting very definitely when insulation is in a condition to break down, before it actually does break down, by a fairly simple measurement of power factor and losses.

Mr. Peek's paper brings out a new method. It gives us a new rule. With each new instrument we enter a new field of investigation, and I am very sure that this paper marks the beginning of a very important era of work along these general lines.

Chester L. Dawes: Mr. Peek has produced some very interesting and important results, but I should like to add to, or amplify some of the explanations which he presents. In Fig. 6 which shows the spark over between concentric cylinders, the 60-cycle curve gives low values of voltage for small values of r; these values increase to a maximum with increase in r after which they decrease. That is, the greater thickness of air has a lower dielectric strength than the thinner layer until a certain ratio of R/r is reached. At first this does not seem reasonable, but the following explanation to me seems rational. The impressed voltage

$$E = \frac{g\,x \log_{10} R/r}{0.434}$$

where g is the gradient at which air breaks down, and x is the radius to the air where the gradient is g. This assumes that the corona has the effect of increasing the diameter of the conductor to x. If this assumption were correct the voltage E could be increased until $x = \frac{R}{\epsilon}$ before spark over would occur. Therefore it would seem that the spark over voltage would be the same for all central conductors whose radius $r \leqq \frac{R}{\epsilon}$. That is, the relation if plotted would be similar to the upper d-c. curve shown in Fig. 6. However the corona surrounding the central conductor is not the same as a metallic conductor of the same diameter for no corona would exist about the metallic conductor. The corona formation about the smaller wires is emitting ions that are projected into the outside layer of air which is supporting the stress. These ions produce others by collision, etc. and the outside layer of air breaks down at a much lower voltage than it would if the corona formation had acted like a metallic conductor. The smaller wires produce a larger number of these ions and a lower spark-over voltage results as shown in Fig. 6. I should like to ask if any reason can be given for the d-c. voltage following a different law than the a-c. in Fig. 6.

As Mr. Peek states, solid insulation like cambric may behave quite differently when tested with d-c. than it does when tested with a-c., which partly is due to the fact that the insulation is composed of an infinite number of minute capacitances and conductances arranged in various series-parallel combinations. When a direct current is impressed across a piece of insulating material there is an initial rush of displacement current which drops off very rapidly at first and then more slowly until after some time it reaches an essentially constant value. This decay of current is almost logarithmic. It may be several minutes before the current reaches its constant value. The above phenomenon is often called "absorption." It is due to the minute condensers constituting the insulation, being charged through high resistances. Therefore the voltage distribution in the insulation will be materially different at the end of charge than it is at the beginning and with alternating current. At the end of charge the distribution is determined entirely by the conductance relations in the insulation and at the beginning of charge and also with alternating current the distribution of potential is determined almost entirely by the capacitance relations in the insulation. It would seem reasonable therefore to find the short time d-c. tests checking more closely than the a-c. tests. The fact that they do not, I should say was due to the fact that the period of two seconds or so was long enough for the direct-current distribution of potential to assume very nearly the final steady state.

The author shows that d-c. breakdowns are practically the same as the a-c. breakdowns when the insulation has a low resistance. Outside the question of the alignment of moisture particles, I believe that the explanation lies again in the manner in which the potential distributed itself through the insulation. When the resistance is low the a-c. distribution of potential is determined more by resistance than it is by capacitance, so the breakdown should be more nearly the same as it is with direct current. This is also true in transil oils. The best grades have a much lower insulation resistance than other well-known solid insulators. Also the oil molecules being mobile, can quickly arrange themselves to make the capacitance a maximum. Therefore little "absorption" can be found in oils.

I should not recommend that direct current be used for testing cables except perhaps in a few instances. It might be applied to homogeneous single-conductor cables provided that sufficient allowance be made to account for unknown hysteresis effects and the foregoing factors. I believe that the heating is negligible at ordinary frequencies. It would be out of the question to test graded cables and the ordinary twin-conductor and multi-conductor cables with direct current, as the voltage distribution throughout the various insulations when in service is determined by the capacitance relations, whereas, in the d-c. testing it would be determined by conductance relations.

Clayton H. Sharp: As I understand it, Mr. Peek advocates the use of continuous voltage for cable testing for the reason that under certain conditions the continuous voltage is more severe on the cable than the alternating voltage, whereas yesterday, he objected to the use of the high-frequency oscillatory voltage in testing transmission insulators for the same reason.

John B. Taylor: Has comparison been made between the voltage as determined by the transformer ratio; by electrostatic voltmeter; and by what, at first sight, would be the normal way to measure the high d-c. voltages,—plenty of resistance and standard d-c. voltmeter?

In work with extra high-voltage alternating current there has been much doubt as to the correctness of the values of high voltages, so it is surprising to see in a presentation of d-c. high-voltage experiments the reliance which is placed on a-c. instruments, ratio of transformation and the electrostatic voltmeter.

The Thury system of d-c. series high-voltage transmission of power has been referred to. Service experience in Europe extending over a number of years has demonstrated the practicability of working underground cables and other insulators under continuous voltages higher than has been attempted with alternating current. This advantage of the Thury system from the insulation standpoint has been well recognized and there are other advantages such as opportunity to save copper by using earth-return circuit without inductive disturbances to telegraph and telephone lines. Lack of flexibility in distribution to many consumers unfortunately has interfered with more general introduction of the system. Mr. Peek's curves in Figs. 12 and 13 indicate how much more a cable may be expected to stand under d-c. stress than a-c. stress. Similar tests should be made on completed cable samples containing splices and for much longer time than the 1500 seconds.

Continuous high voltages (higher even than the 150 kv. of the paper) have long been available from "friction" and "influence" electrostatic machines. Large numbers of small storage cells have been connected up, and series of small d-c. generators have been assembled for experiments and testing at voltages at one time regarded extremely high. The complication of many small d-c. generators and the bulk, unreliability and small power output from static machines possibly makes the use of a-c. generators with step-up transformer and rectifying "kenetron" the most practicable high continuous d-c. experimental device.

Cable failures occur principally at splices due to,—cracked insulation from bending and handling; damaged insulation from overheating (drying out, soldering, lead wiping, or hot compound);

insufficient insulation thickness or poorer grade at splice than in run of the cable; introduction of moisture; presence of air cavities (possibly at reduced pressure resulting from contraction of compound on cooling.)

These different weaknesses probably have different ratios for standing a-c. and d-c. stresses. Particularly an air space in the field between conductors might be expected as result of continued thermal or chemical local action to fail more readily on a-c. stresses. Mr. Peek suggests testing cables with direct current of value equal to maximum of accepted a-c. testing values. His results in Figs. 12 and 13 would seem to call for a higher direct current than this. Perhaps twice the effective a-c. voltage would be comparable.

F. W. Peek, Jr.: Referring to the questions of Dr. Whitehead and Mr. Taylor, the voltages were checked by means of a known liquid resistance in series with a milliammeter, and also by a known resistance in series with an oscillographic vibrator, across the high-voltage lines.

Dr. Sharp misunderstood my remarks on "high frequency." I think my meaning will be clear when reference is made to the written discussion.[1] I did not condemn high-frequency tests, as such, but gave an illustration to show how easy it is to misinterpret the results of such tests.

I have not advocated direct current for cable testing. I have simply pointed out that it looks very promising, for the following reasons:

I. Air, oil and insulating liquids break down at d-c. voltages equal to the maximum a-c. voltages.

II. Solid insulations containing moisture break down at approximately the same maximum voltages on alternating and direct current.

III. Solid insulation, *in good condition*, require a direct-current voltage much higher than the maximum alternating-current voltage to cause breakdown.

It thus seems that most faults will be located equally well on a-c. or d-c., if a d-c. voltage equal to the maximum of the a-c. testing voltage is used. This follows because large cracks filled with air or oil will be broken down at the same maximum voltage on a-c. or d-c. (see I above); wet insulation will break down at approximately equal voltages on a-c. or d-c. (see II above); injury is much less likely to occur to solid insulation in good condition on d-c. (see III above).

Although the laboratory tests indicate very promising results, I believe it important that practical experience be gained in the field, before recommendations are made for extensive or general use of this form of testing. Naturally, the principal use of the d-c. test would be in the field where a portable set is necessary. All cables should be given the a-c. test in the factory.

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[1] Discussion of papers of Messrs. Creighton and Marvin, Cleveland, Part 1 this volume.

When the fault occurs in the cable it is often desirable to burn it out to low resistance so that its position can later be located by a bridge. Our laboratory tests indicate that this can be done with the d-c. testing set. The time required to burn out a fault in this way depends upon the condition of the sheath. If the sheath has been broken open a greater time will be required than if the sheath is intact. The time will vary from 1 to 5 minutes.

In making the d-c. corona tests we found, as a rule, that the visual corona point was quite sharp and definite when the wire was positive. When the wire was negative, however, it was often quite difficult to determine this point definitely. The slightest surface irregularities cause the negative corona to brush at fairly low voltage. It is quite possible that the negative corona voltage is a few per cent higher than the positive corona voltage, the exact difference, however, if there is any, will depend to a considerable extent, upon the observer and what is defined as the critical point.

L. T. Robinson: I think one of the greatest advantages in cable testing by direct current is that you can get along without an undue amount of apparatus—you are required to furnish only the energy for testing the cable and not a big charging current, and therefore you do not need a big 50-kw. transformer to test a small cable, but maybe a 3 or 5-kw. transformer, which is a great advantage.

F. W. Peek, Jr.: I wish to say, as a matter of interest, that it may require from 1000 to 2000 kv-a. to test long lengths of cable on alternating current whereas similar tests may be made on direct current with from 3 to 5 kv-a. That is one of the reasons why d-c. testing suggests itself, and why, I believe, it is worth trying out in practise. It will often be a question of a d-c. test or no test at all, and not which is best.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 29, 1916.

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THE CORONA VOLTMETER

BY J. B. WHITEHEAD AND M. W. PULLEN

Abstract of Paper

An instrument is described in which the first appearance of corona is used as a measure of the applied voltage.

Three methods for detecting the first appearance of corona have been developed, in addition to the method of visual observation. These methods involve the use of the electroscope, the galvanometer, and the telephone respectively.

For a given wire, in fixed relation to the opposite side of the circuit, corona-forming voltage depends on the density of the air, that is, on the pressure and temperature. The corona voltmeter consists of a grounded metal cylinder, with a central conductor on which corona is formed. Both cylinder and conductor are enclosed in a larger, air-tight cylinder, in which the pressure can be varied by a hand pump. This variation in pressure provides the means by which a wide range of voltage reading is possible. The calibration of the instrument is absolute, that is, can be calculated, or may be obtained by comparison with existing standards.

The voltmeter is set for a given voltage by adjusting the pressure to a value calculated from the dimensions of the instrument and taken from a calibration table or curve. When the ascending voltage reaches the value for which the voltmeter is set, corona begins, and this is sharply indicated by any one of the three methods mentioned. To measure an unknown voltage, the pressure is gradually lowered from some higher value and is read at the instant corona appears. A table of calculated values, or a calibration curve then gives the unknown voltage.

Tests showing the constancy and permanence of the instrument are described.

Introduction

DURING a number of years' intermittent experiment on the phenomena attending the electric break-down of air, one of the most striking observations has been the extreme sharpness, in an ascending range of voltage values, with which this break-down occurs in the form of corona on clean round wires. Under suitable conditions of observation, critical voltage readings repeat themselves to an accuracy equal to that within which the usual direct reading instrument can be read, *i.e.*, of the order of one-tenth of one per cent. This fact has led one of the authors in his papers[1] describing the experiments, to point several times to its value as a method for measuring high voltage. It has been shown beyond question that the appearance of corona depends on the maximum value of the alternating current wave.

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[1] For references see bibliography at end of paper.

That the visual appearance of corona might be used as a means of measurement of the maximum value of the voltage wave was apparently first suggested by H. J. Ryan[2] in his notable paper of 1904. His suggestion, however, does not seem to have extended beyond the visual observation of the light given out by corona, which naturally is only visible in darkness. Reliance on visual observation therefore, practically precludes the use of the method except perhaps for laboratory purposes. This and the fact that the correction factors for variations of temperature and pressure have only recently been definitely fixed[3], probably explains the absence of attempt, up to this time, to make use of the appearance of corona as a measure of voltage.

The fact that air in the neighborhood of the corona is ionized, that is, possesses high electric conductivity, has been extensively utilized by one of the authors[1] as a means of detecting the presence of corona. A charged electroscope in a suitable location near a high-voltage conductor discharges with marked suddenness on the appearance of corona. The electroscope, then, may be used as a detecting instrument free from the limitations of visual observation of the light of the corona. Other means of detection have also been developed and will be described in this paper. With a suitable detecting instrument therefore the corona becomes far more accessible as a high-voltage indicator.

Little need be said as to the importance of a convenient and reliable method for measuring the maximum value of high alternating voltage. The question is answered by the fact that the electric strength of all insulating material is dependent on the maximum value of applied voltage. The needle gap as a means of measurement may also be passed with only brief comment. Although long the standard of the Institute, its unreliability is now universally recognized. It may be stated, however, that under properly chosen conditions and with points having angles greater than 20 degrees, quite uniform results may be obtained. The thorough investigation of the needle gap by Weicker[4] has shown its limited value and many weaknesses.

The sphere gap has been strongly advocated as an instrument free from many of the objections to the needle gap. The authors of this paper cannot claim familiarity with this instrument, and therefore, hesitate to call attention to its apparent limitations. It is fair, however, to point out that the results of different observers using the sphere gap are not in agreement, that the results of a single observer frequently differ by several per cent, and that as shown by Peek[5], the calibration curve is widely different for the cases of both terminals insulated, and one terminal grounded. Its accuracy therefore is very sensitive to the proximity or presence of other objects in the neighborhood, due to their influence on the electrostatic field. Attempts have also been made to derive mathematical expressions from which it should be possible to calculate the spark-over voltage of any given sphere gap. However, the results of Russell[6] in this direction have been attacked by de Kowalski and Rappel[7], and the subsequent discussion indicates that there is considerable doubt whether it is possible to calculate accurately the electric intensity within the sphere gap. Therefore notwithstanding the adoption by the Institute of the sphere gap as a standard, no apology is necessary in describing an instrument which seems to be free from some of its imperfections.

Recent papers before the Institute by Chubb[8] and by Sharp and Doyle[9] have described crest voltmeters utilizing the rectifying properties of hot cathode tubes. The arrangement proposed by Sharp and Doyle is especially simple and promising. Both types should prove valuable for low-voltage readings although the use of a vacuum tube is an undesirable feature for general utility. On high voltage, series condensers or resistance are apparently necessary, and therefore introduce well-known uncertainties.

PRINCIPLE OF THE CORONA VOLTMETER

The corona as a means of measurement possesses the great advantage that it obeys a definite law upon which close agreement now obtains among many observers. If it is possible to foretell with a good degree of precision the value of voltage at which corona will begin on a clean round conductor, an absolute calibration is therefore also possible. This paper describes an instrument in which the first appearance of corona may be accurately and conveniently detected, and which may be set readily and without trouble for any voltage within a considerable range.

From the nature of the corona it will be evident that an instrument using it as an indicator of voltage can make no pretense to a direct-reading scale. No more can the needle gap or the sphere gap. The corona voltmeter as now described, however, possesses, among other advantages, two important features, which in the absence of a direct-reading scale, are very good substitutes. (1) Convenience of observation. (2) A wide range of voltage without manipulation or adjustment of the instrument.

METHODS OF OBSERVATION

The appearance of corona obeys a rigid law only when the wire or rod on which it appears is accurately placed on the axis of a hollow cylinder forming the opposite side of the circuit. This arrangement has therefore been chosen for the voltmeter. In the present form the outer cylinder is grounded, thus presenting the advantage of screening the wire from outside influence and permitting close approach to it without danger.

Three methods of observing the beginning of corona, not including visual observation, have been developed; the electroscope, the galvanometer, and the telephone.

The Electroscope. The electroscope is the most sensitive instrument for detecting the state of ionization or conductivity in a gas. Since the corona is attended by copious ionization the use of the electroscope for detecting corona involves only the question whether the electroscope can be brought into suitable proximity of the corona without disturbing the electric field upon which the formation of the corona depends.

If the outer grounded cylinder surrounding the rod or wire on which the corona is formed is perforated with a few small holes, and an insulated electrode connected to a charged electroscope is brought up close to these holes on the outside, the first appearance of corona causes an immediate discharge of the electroscope. The close coincidence between the appearance of corona and the electroscope leak or discharge was described in the first paper of one of the authors, on the "Electric Strength of Air."[1] So copious is the ionization with the very first appearance of the visual corona that it is not necessary to use a particularly sensitive electroscope. A roughly constructed instrument using a large strip of aluminum foil instead of gold leaf has been used with good advantage.

In order to meet the possible requirement of moving from place to place, a portable electroscope has been developed. This instrument has only one leaf which, in its zero or discharged position, rests against a rigid member. Means are provided whereby in this position the leaf is pressed throughout its entire length against the rigid member by a flap made of the paper which separates the successive layers of gold leaf in the books in which the leaf is usually furnished. This flap is readily adjustable from outside the instrument, which can thus be handled without danger to the gold leaf. The instrument is also furnished with means for adjusting the sensibility. Since the strip of gold leaf swings through a circular arc it may be calibrated, although this is not necessary for the purpose of indicating the first appearance of corona. Direct visual observation of the discharge of the electroscope is possible but is not as accurate as when it is viewed through a telescope.

The electroscope may be charged from a 120-volt, direct-current circuit, either directly or by a parallel-series connection of small condensers.

The Galvanometer. If the outer grounded cylinder be drilled with small holes fairly close together over its entire surface, and if the electrode formerly used for the electroscope be extended in area so as to form an outer cylinder surrounding that forming one side of the high voltage circuit, a very greatly increased volume of ionized gas may be utilized. If this outer cylinder or electrode is brought close to the grounded cylinder and is connected to ground through a galvanometer and source of continuous potential, the galvanometer should deflect when the gas between the two cylinders is ionized. The outer or electrode cylinder must of course, be carefully insulated.

The object of this arrangement is to detect the presence of corona with a less sensitive instrument than the electroscope. The results as described below indicate that under proper conditions this arrangement serves admirably for its purpose. In the larger of the two voltmeters to be described, a portable needle galvanometer with a direct reading scale and sensitivity of 10^{-5} amperes may be used. For the smaller voltmeter a more sensitive galvanometer is necessary. Up to this time a reflecting galvanometer with telescope has been used, of sensitivity in the neighborhood of 10^{-7} amperes. The magnitude of its deflections indicates that the more sensitive forms of needle galvanometer may, if necessary, be used with this instrument also. For portable purposes, the needle galvanometer is obviously the more desirable.

A continuous voltage is necessary in the use of the galvanometer. The 240-volt, three-wire circuit has been used in the experiments, provision being made for 120 volts positive or negative on the galvanometer and electrode. The arrangement is markedly more sensitive for negative than it is for positive electrode, owing to the differences in the properties of negative and positive ions and consequently the resulting values of the ionization currents.

The Telephone. The corona emits a sound which is gathered and intensified if the region surrounding the corona forming wire is enclosed. Earlier experiments showed that if the perforated grounded cylinder or corona tube has its ends capped and is enclosed in an outer jacket of any kind provided with a single hole to which the ear may be placed, the first appearance of corona is attended by sound of considerable volume. If a cone, connected by tubes to ear pieces is added, the sound is further intensified, and in fact, becomes quite loud.

As described below, the corona voltmeter in its present form involves a variation of the gas pressure in the corona tube. This of course, will prevent a direct listening to the sound. In order therefore, to take advantage of the sound, a telephone transmitter has been inserted into a side tube and connected with twin receivers in the usual head-piece form, on the outside. Obviously gas pressure has no influence on the proper operation of the telephone transmitter. This arrangement has been found to work admirably, and indeed, has been found quite as reliable as either of the foregoing methods for indicating the initial presence of the corona.

Visual Observation. Any of the foregoing methods may be checked in a darkened space by visual observation. In the present work the two forms of instrument have been provided with plate glass disks at their ends, permitting detection of the first appearance of visual corona. As numerous tests have shown that the indications of all three of the foregoing methods are simultaneous with the appearance of corona, the use of the visual method has been limited to the purposes of inspection and checking.

RANGE OF OBSERVATION

At atmospheric pressure and temperature, a given diameter of wire or rod, placed in a given outer tube, will form corona at one and only one definite value of voltage. Hence to obtain any range in an instrument using corona under atmospheric conditions would require a change in the diameter of the outer cylinder or of the inner conductor, or in the use of a wire or rod of varying diameter. A change from one conductor to another is not impossible but is manifestly troublesome and objectionable, save perhaps, under laboratory conditions. The use of a conductor of varying diameter is not feasible on account of the small temperature variations due to the presence of corona and on account of the necessity of visual observation.

Corona-forming voltage depends on the pressure and temperature of the air. The values of the voltage at which corona forms on a given wire under any conditions of temperature and pressure are now well-known. The density of the gas is the determining factor and variations of density cause quite wide differences in the value of the corona forming voltage.

A prominent feature of the corona voltmeter as here described is that the pressure in the corona tube is controlled and varied and constitutes the means whereby the instrument is set for a given voltage. Adjustment of the pressure throughout a wide range is quite easy and thus provides practically any desired range of voltage value. In this way values of air density which necessitate a troublesome correction at atmospheric pressure, are eliminated, and in fact, are turned to account in providing a ready means of extending the scale of the instrument. One wire or rod serves for the whole range, and no adjustments other than that of the pressure are necessary. There is in fact, no limit to the range other than that due to the insulation of the air tight bushings, through which connection is made to the corona forming rod, and that set by a safe gas pressure within the instrument. In the two forms of instrument described below, in the smaller a working range between 20,000 and 50,000 volts is obtained with a pressure of 30 cm. below, and 60 cm. of mercury above, atmospheric pressure. A corresponding range with 100,000 volts as a maximum and the same range of pressure is obtained in the larger instrument.

DESCRIPTION OF VOLTMETERS

100,000-VOLT TYPE

The first type, designed after a number of preliminary experiments, for a range of 100,000 volts is shown in Fig. 1. It consists of an outer steel shell 45.7 cm. outside diameter and 44.4 cm. inside diameter. The ends are enclosed with plate glass disks 1.9 cm. thick, held between flanges, and each supporting in a hole in its center a 100,000-volt porcelain bushing. This outer shell provides a chamber in which the pressure may be varied; the voltmeter proper is inside. The picture shows some of the various terminals and auxiliary apparatus. The length of the outer shell over flanges is 190 cm. The length of the whole instrument over insulator bushings is 238 cm.

Fig. 2 is a descriptive drawing showing the various parts. In order that certain features may be emphasized no attempt has been made to make the drawing to a uniform scale. The central conductor on which corona is formed, shown at *A*, consists of about 40 in. (101.5 cm.) of Stubb's tool steel, 0.635 cm. in diameter. At either end, just outside the cylinder *B*, the central conductor is suitably joined to rods of larger diameter which extend through the porcelain bushing *E* at either end. The object of this enlargement is to make certain that the electric discharge occurs only within the region inside cylinder *B*. This outer cylinder *B* is 92 cm. long, 30.7 cm. in diameter, is perforated over its entire surface with holes 1.58 cm. in diameter, and is electrically connected to the outer shell *C*, which is in turn connected to earth. The insulators *E* are cemented to the glass disks *D*, which in turn are held between soft rubber gaskets and the flanges on the outer tube. The final centering of the central conductor is accomplished at the ends of the insulators, the central openings of which provide free play for this purpose. *F* is a thin metal cylinder surrounding, and very close to, the perforated cylinder *B*. It is insulated and connects through a sulphur bushing with the galvanometer *G* and a source of continuous potential *S*. *H* is a small electrode fitting in a hole in *F* but not touching it, and connected through a sulphur bushing with an electroscope, *I*, whose case is connected to earth. *J* is

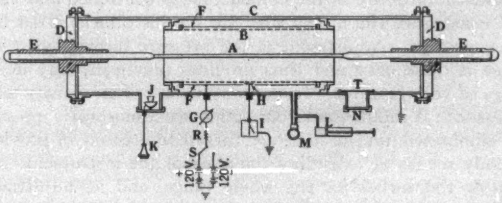
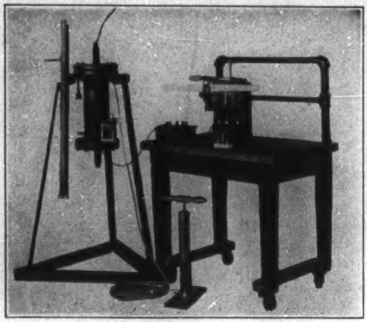
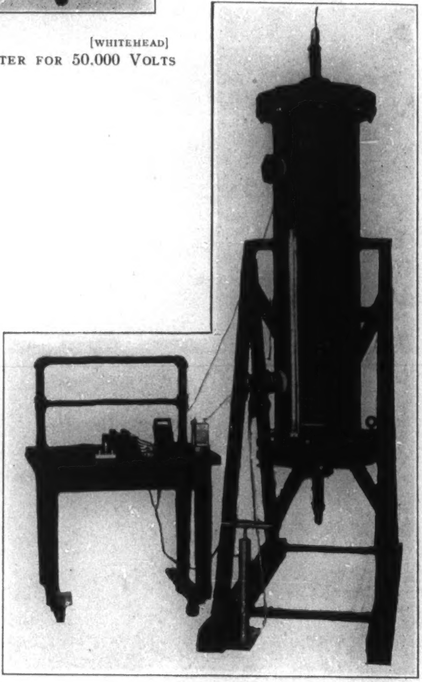


Fig. 2—Corona Voltmeter for 100,000 Volts—Central Section and Connections of Auxiliary Apparatus

PLATE LIV.
A. I. E. E.
VOL. XXXV, 1916



[WHITEHEAD]
FIG. 3—CORONA VOLTMETER FOR 50.000 VOLTS



[WHITEHEAD]
FIG. 1 CORONA VOLTMETER FOR 100,000 VOLTS

a telephone transmitter fitting into a side tube shown in Fig. 1. *L* is an ordinary hand air pump for either pressure or vacuum; together with the gauge *M* it is connected to the main containing cylinder. *N* is a small side tube with glass top through which the thermometer *T*, recording temperature inside the tube, may be observed. All permanent joints were sealed with a cement made from litharge and glycerine, while those holding the glass and cap nuts on the end of the central conductor consisted of soft rubber gaskets. No particular care was given to the elimination of unnecessary joints, and it has been found possible to maintain pressure as high as 60 cm. above atmosphere over periods quite sufficient to insure constancy of observation.

In designing the instrument as described above, liberal allowances were made in all dimensions. It was the first instrument in which pressure was applied and in order to provide also for thorough inspection and access to all parts, it was realized that it would probably be found unnecessarily large. This proved to be the case. The indications of the appearance of corona by the several methods already described were so satisfactory that it was soon found that the instrument could be made smaller without sacrifice of reliability.

The only limitation which has been found in this first type of instrument is in the insulation. If too large a central conductor is used, say above 1.75 cm. diameter, the high voltage required to start corona causes a spark between the conductor and the outer casing at the edge of the insulator bushing due to a region of high electric intensity. This trouble is entirely eliminated by the use of a smaller corona conductor, with ends of larger diameter, as already described. Corona then appears at lower voltages at atmospheric pressure and the spark-over voltages at the bushing are never reached. The voltage at that point only rises when pressure is on the tube and sparking is then suppressed.

The pressure in this tube has only been carried to 62 cm. of mercury. This means a total thrust of 2100 lb. (952.5 kg.) on each of the plate glass disks at the ends. While the central conductor can probably be relied on to take up a part of this thrust the pressure has not been carried higher up to this time for fear of breaking the glass disks. It is not necessary to have the whole end of the tube of glass, as small openings only are required for observing visually, the appearance of corona. Therefore, in a tube of the general dimensions given, it should be quite easy to reach pressures far in excess of that mentioned. Our experience indicates that the chief limitation of the instrument is the insulation of the bushing leading the voltage to the central corona forming conductor.

50,000-VOLT TYPE

As a result of the experiments with the foregoing instrument, another was designed for 50,000 volts in which effort was made to reduce the dimensions without impairing its reliability. Fig. 3 shows a general view. In all respects the details of the instrument are the same as those already described in connection with the larger type, except that is this smaller type the telephone has been omitted. This was done largely because of the difficulty and time required for setting into the outer cylinder a branch tube large enough to hold the telephone transmitter, the diameter of the main cylinder being only 12.7 cm. Observations are in no wise dependent on the use of the telephone and this was not considered as a necessary feature for an experimental type of instrument.

The principal dimensions for the smaller instrument are as follows: Outer tube, 12 cm. inside diameter, 24 cm. diameter over end flanges, length over flanges, 52 cm., length over all, 76 cm. The inside or corona tube is 9.51 cm. inside diameter and 29 cm. long. Central conductors or rods of various diameters have been used. In the experiments described below the rod was of tool steel, 0.396 cm. in diameter.

In this instrument as in the other, the limit has been found in the insulation of the end bushings. In the form shown, brush discharge begins at 65,000 volts over the inside surface of the glass ends. As the insulators were home-made, by making the whole instrument somewhat longer, and improving the insulation, there seems to be no reason why this instrument could not be used for even higher values. The pressure required to reach above 50,000 volts was only 66 cm. of mercury above atmosphere.

Pressure is adjusted and varied in the tubes without trouble by means of an ordinary hand pump, for both vacuum and pressure, about 46 cm. long, and of the type used for bicycle and automobile tires. A valve with small opening permits easy adjustment of pressure.

OBSERVATIONS AND TESTS

Power was taken from a 10-kv-a., 100,000-volt transformer fed by a 7.5-kv-a., motor-driven, smooth body, surface-wound, single-phase generator, specially designed to give a smooth wave. The set was designed for frequencies between 45 and 120 cycles and was equipped for close speed and generator field control within wide ranges.

Throughout the experiments a frequency of 60 cycles was maintained. Variation of the transformer primary voltage was accomplished by varying the field current of the generator.

The transformer is of the core-type, having all of its coils wound on one side of the magnetic circuit of rectangular shape. It is provided with two primary coils, each for 110 volts. It also has a tertiary coil with the same number of turns as one primary coil. All of these coils are close to the core. The high-tension winding consists of a large number of pan-cake shaped coils set side by side over the primary and filling a large portion of the central opening of the magnetic circuit. The transformer was designed for operation at any frequency between 20 and 120 cycles. The ratio of high-tension to tertiary coil turns is 833.36.

All observations have been made with the outer tube of the voltmeter, one end of the tertiary coil, one end of the primary and one end of the high-tension winding all connected to ground. In the observations of the smaller voltmeter the primary coils were connected in series while on the larger they were in parallel The value of the generator voltage in both cases ranged from 20 volts up to about 100. It will be seen therefore that all observations were taken at comparatively low values of the magnetic density in both the generator and transformer. Power for the direct-current motor and also for the generator field was taken from a storage battery, giving most of the time practically perfect conditions as to constancy.

The general method of taking observations was, with secondary connected to the central conductor of the voltmeter, to raise the voltage gradually, observing the electroscope and galvanometer, and listening with the telephones, singly or all together Simultaneous readings of all three were possible by using a reflecting galvanometer, and throwing, with suitable mirror arrangements, the image of the electroscope leaf into the telescope used for reading the galvanometer. As soon as any one or all of the instruments indicated the appearance of corona the voltage was read by an electro-dynamometer type of voltmeter on the terminals of the tertiary coil of the transformer. A large number of oscillograms were taken during the course of the experiments which, with the voltmeter readings, serve to give the crest factors of the voltages in the tertiary coil.

Special interest attaches to the extreme constancy with which the corona is indicated by any one of the four methods described and to the closeness with which the four methods agree among themselves.

The readings in Table I were taken by two observers. One observer would read the electroscope or galvanometer or listen with the telephone while gradually raising the voltage. As soon as indication of corona appeared he would tell the other observer to read the voltage. The voltage would then be lowered by an indeterminate amount and the process repeated. The readings with each type of indicating instrument were taken singly, the several sets following one immediately after the other.

As a general thing the electroscope leaf would stand apparently perfectly still, its normal rate of leakage being extremely small. With the appearance of corona the leaf would discharge in periods varying between one and five or six seconds depending upon the size of the conductor and the condition of its surface. The rate of leak attendant upon the appearance of corona is always sharply marked, and there is no difficulty in distinguishing it even when at its slowest.

TABLE I.

COMPARISON OF ELECTROSCOPE, GALVANOMETER, AND TELEPHONE AS INDICATORS OF PRESENCE OF CORONA

	Critical volts on tertiary coil. 0.633 cm. diam. rod in 30.7 cm. tube					
Electroscope.......	48.75	48.75	48.8	48.8	48.75	48.75
Galvanometer. ...	48.8	48.8	48.75	48.8	48.75	48.7
Telephone.........	48.8	48.8	48.75	48.8	48.8	48.75

The galvanometer deflection is also sharply marked. With the approach to corona voltage the galvanometer stands at zero or with a small deflection due to leakage over the insulation of its electrode, the deflection being practically constant. With the appearance of corona the galvanometer takes a sharp increase of deflection the amount of which is dependent upon its sensitivity. In the mirror galvanometer already mentioned, the amount of this sudden deflection was 6.5 mm. No fine adjustment of the voltage increase could bring the deflection below this value. With the less sensitive needle galvanometer already described, the deflection was considerably less, of the order of one mm. which, however, is readily detectable. These deflections increase rapidly with even a small increase of the voltage above the corona forming point.

With reference to the telephone, it has already been stated that with the approach to corona voltage there is no sound in the telephone, but the instant corona appears a very pronounced note is heard.

A number of preliminary tests with various sizes of central conductor were made on each type of voltmeter. These tests had as their principal object the study as to how the values obtained would agree with the formulas given by various experiments connecting the critical surface intensity of a conductor with its diameter and with the temperature and pressure.

TABLE II.

COMPARISON OF OBSERVED AND CALCULATED CORONA VOLTAGES

Diam. rod cm.	Critical volts			δ	Critical surface intensity	
					Obs.	Calc.
0.238	21.6	21.7	21.8	1.014	59,400	59,800
0.317	24.6	24.7	24.6	1.014	55,500	55,400
0.396	27.6	27.6	27.6	1.017	53.800	54,000
0.477	30	30	29.9	1.017	50,700	51,200

The method followed in these tests has been the same as that used by one of the authors in his papers on "The Electric Strength of Air." This method involves the reading of the critical voltage on the low-tension side, the measurement of the wave form on the low-tension side, and the assumption that the ratio of transformation of the transformer is that of the number of turns in primary and secondary. This method has been found to give very uniform results for moderate values of the secondary voltage.

Table II shows the results with four sizes of rod in the smaller voltmeter. The results calculated from the expression for the surface intensity,

$$E = 32\left(\delta + 0.296\sqrt{\frac{\delta}{r}}\right) \text{kv/cm.} \tag{1}$$

are also given in one column of the table. It will be seen that the agreement is quite close. The constants of the above expression are those which were first proposed by one of the authors. Peek's corresponding expression gives a value in the neighborhood of 31 instead of 32 for the principal factor of the right hand member of the expression. Further evidence, leading to the conclusion that the higher value is the correct one, is given in our results below in which the density of the air is varied through wide limits.

A number of tests were also taken with various sizes of central conductor in the larger voltmeter. The observations were taken under the same conditions of accuracy and care, and could also be repeated as often as desired. The values of voltages, however, as read on the low-tension side, and reduced to the high-tension side in the method described, were always lower than the values calculated from the expression just given. This discrepancy was found to be due to a rise in voltage in the secondary circuit, owing to its leakage reactance and to the charging current of the larger voltmeter, this rise having no equivalent in the tertiary coil.

The primary current of the transformer increased from 2.9 to 4.3 amperes on connecting the larger voltmeter, the power input of the primary remaining practically unchanged. The arrangement of the coils in the transformer has already been described and indicates clearly the probability of leakage reactance in the high-tension winding which has no counterpart in the tertiary coil on which the voltage was read.

CALIBRATION

The calibration of any of the types of instrument heretofore used for measuring crest voltages has always been an uncertain factor. The usual method has been comparison with a standard needle or sphere gap, or with low-voltage voltmeter readings corrected for crest factors. But, as is well known, both types of spark gap must themselves be calibrated, since it is not certain that even the sphere gap will break down at a voltage which can be calculated in terms of the separation and the diameter of the spheres. It is now stated, with considerable confidence, that a tertiary coil can be so wound in a high-tension transformer that it will reflect accurately the value and wave form of the voltage in the high-tension winding. While this may be true, the evidence is still lacking, and the reason is that there is no certain method of measuring the high-tension voltage directly in terms of laboratory standards.

It is the opinion of the authors of this paper that the desired standard of voltage for values above 10,000 or 15,000 is available in the corona forming on a clean wire centered in an outer cylinder. All observers are now agreed that corona forming voltages repeat themselves with the greatest degree of accuracy under the same conditions of temperature and pressure, and further, the variations due to temperature and pressure are now understood. The constants which give the actual value of critical corona voltage for a given size wire as determined by different observers, agree very closely. It would appear then, that the only thing necessary to fix an absolute standard of high voltage is the formation of a committee who should conduct, under properly considered conditions, a series of experiments for the determination of the figure for the electric strength of air which could be used as a standard. This quantity is undoubtedly a definite physical constant, and it is only necessary to eliminate all source of error in experiment to determine it accurately.

The corona voltmeter as already described, can of course, be calibrated by exactly the same means which are used for the calibration of the standard spark-gaps. In view, however, of the uncertainty of such calibration, the authors have preferred to compare the indications of the instruments with values of corona forming voltage as deduced from formula (**1**), in which E is the electric intensity at the surface of the wire, at which corona is formed, in kilovolts per centimeter, and δ is the density factor given by the expression

$$\delta = \frac{3.92 \times p}{273 + t} \qquad (2)$$

in which p is the pressure in cm. of mercury, and t is the temperature in centigrade degrees. The constants of formula (**1**) have been checked a number of times by one of the authors. The values found by Peek and others are in close agreement.

50,000-*Volt Type*. In Table III, are given the results of a series of observations with varying pressures on the smaller type of voltmeter. The readings taken were: voltage on the tertiary coil, air pressure, as measured on a mercury pressure gauge, temperature inside the tube, and oscillograms of the tertiary coil voltage in order to obtain the crest factors. The oscillograms have an average amplitude of 2.2 cm., and a length at the base of about three cm. The ordinates were measured at distances of one mm. As so measured, the crest factors varied uniformly between 1.45 and 1.44, over a range of tertiary coil voltage from 20 to 45 volts covering the range of observation.

The values of the corona surface intensity, as observed and also as calculated from the expression given above are given in the last two columns of the table. In Fig. 4 a curve is drawn between the critical surface intensity and the density factor. The solid curve gives the relation as calculated, and observed values are indicated by crosses. It will be observed that at higher values of pressure the observed values are slightly lower

TABLE III.

OBSERVATIONS WITH 50,000 VOLTS CORONA VOLTMETER

Pressure cm.		Temp. deg. cent.	δ	Ter. Coil volts		Crit. surf. intens. volts per cm.		Max. volts
Obs.	Corr.			Eff.	Max.	Obs.	Calc.	
− 34	43.5	27	0.569	17.8	25.9	34,390	34,200	21,580
− 33	44.5	27	0.581	18.	26.2	34,760	34,800	
− 32.8	44.7	27	0.584	18.2	26.4	35,120	34,940	....
− 26.9	50.6	27	0.661	20.	29.1	38,600	38,450	....
− 26.4	51.1	26.5	0.668	20	29.1	38,600	38,750	24,200
− 25.8	51.7	26.5	0.676	20.3	29.5	39,150	39,120	....
− 17.5	60	26.5	0.785	22.8	33.1	43,920	43,760	....
− 17.2	60.3	26.5	0.789	22.8	33.1	43,920	43,920	....
− 17.	60.5	26.5	0.791	22.9	33.2	44,140	44,000	27,700
− 11.8	65.7	26.	0.861	24.4	35.4	47,000	47,300	....
0.	74.7	26.	0.979	27.	39.1	51,950	52,350	....
0.	74.7	20.5	0.997	27.5	39.8	52,900	53,150	....
+ 15.	86.9	20.5	1.160	30.7	44.5	59,020	60,050	37,100
15.3	87.2	20.5	1.164	30.8	44.6	59,220	60,200	....
25.2	97.1	21.	1.294	33.7	48.8	64,750	65,600	....
26.3	98.2	21.	1.309	34.	49.2	65,350	66,200	....
27.7	99.6	21.	1.327	34.4	49.8	66,050	66,900	41,500
33.4	105.3	22.	1.4	35.9	51.9	68,900	69,000	....
34.2	106.1	22.	1.410	36.2	52.3	69,400	70,000	....
38.3	110.2	23.	1.460	37.3	53.9	71,600	72,400	....
38.6	110.8	23.	1.468	37.5	54.2	71,900	72,700	45,100
45.1	117.	23.	1.549	39.2	56.6	75,200	76,000	....
45.9	117.8	23.	1.560	39.5	57.0	75,700	76,400	....
53.1	125.	24.	1.650	41.5	59.9	79,500	80,100	....
54.2	126.1	24.	1.664	41.8	60.3	80,050	80,700	50,300
56.7	128.6	24.	1.697	42.2	60.9	80,800	82,000	....
60.7	132.6	25.	1.744	43.5	62.7	83,250	83,800	....
61.9	133.8	25.	1.760	43.6	62.9	83,480	84,500	....
63.3	135.2	25.	1.778	44.0	63.4	84,700	85,200	52,800
66.	137.9	26.	1.807	44.8	64.6	85,700	86,400	53,800

than those calculated. This is partly due to the fact that the observations were taken with very slowly-diminishing pressure owing to leaks in the tube. Much time and trouble was saved by closing some of the necessary openings in the tube with rubber gaskets instead of sealing them permanently. These gaskets leaked slowly at the high pressures. It is also possible that a rise in secondary voltage due to leakage reactance and charging current was present at the higher values of voltage.

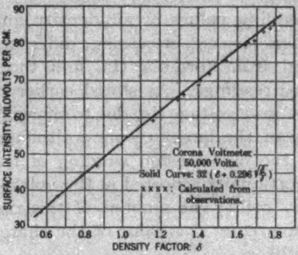


FIG. 4—CALCULATED AND OBSERVED VALUES OF VOLTAGE AT DIFFERENT VALUES OF AIR DENSITY

100,000-Volt Type. The larger type of instrument has been operated with a number of different sizes of central conductor and through the range of pressure between 65 cm. and 136 cm. of mercury corresponding to a range of voltage between 50,000 and 110,000 maximum values. Table IV gives a typical series of observations with a steel rod 0.635 cm. in diameter as the central conductor. The table also contains a column giving the values calculated from the expression for the critical surface intensity as affected by temperature and pressure to which

TABLE IV.

OBSERVATIONS WITH 100,000 VOLT CORONA VOLTMETER

Pressure cm.		Temp. deg. cent.	δ	Ter. coil volts		Crit. surf. intens. volts per cm.		Max. volts
Obs.	Corr.			Eff.	Max.	Obs.	calc.	
− 10.6	64.7	21.7	0.861	40.5	60.7	41,300	43,150	50,600
− 6.4	68.9	21.7	0.918	42.4	63.5	43,250	45,450	53,000
− 5.8	68.9	20.8	0.920	42.9	64.3	43,750	45,500	53,600
0.	74.7	20.7	0.996	45.9	68.8	46,800	48,650	57,400
+ 6.	80.7	20.9	1.076	48.6	73.0	49,580	51,800	60,800
11.3	86.0	21.	1.146	51.1	76.6	52,120	54,650	64,000
16.2	91.0	21.1	1.212	53.4	80.8	54,450	57,400	66,700
21.1	96.0	21.2	1.278	55.7	83.5	56,820	59,850	69,600
27.6	102.5	21.3	1.365	58.4	82.7	59,600	63,300	73,000
33.9	109.0	21.4	1.451	61.1	91.6	62,320	66,550	76,400
37.7	112.8	21.5	1.502	62.9	94.2	64,150	68,600	78,600
43.3	118.5	21.6	1.576	64.3	96.5	65,700	71,350	80,300
48.2	123.5	21.7	1.643	65.9	98.7	67,200	74,050	82,400
55.7	131.0	21.8	1.742	68.5	102.8	69,800	77,900	85,600
61.4	136.7	21.9	1.818	70.8	106.1	72,100	80,800	88,500

reference has already been made. The curves of Fig. 5 show the relation between the critical surface intensity and air density as calculated from formula (**1**) and also values as estimated from the readings of the voltmeter on the tertiary coil.

As will be noted, with ascending values of air density and therefore critical voltage, there is an increasing difference between the values calculated from formula (**1**), and those estimated from the low-voltage readings. As stated earlier in the paper, the explanation lies in a voltage rise due to charging current taken by the capacity of the larger corona voltmeter, and the leakage reactance of the high-tension winding of the transformer, which is not proportionally reflected in the voltage at the terminals of the tertiary coil. The amount of this rise would evidently be greater, the greater the value of the charging current of the voltmeter tube; that is, the higher the value of the impressed voltage. The curve of the observed values, therefore, shows values lower than those actually reached at the high-tension terminals. In the case of the 50,000-volt instrument, owing to the very much smaller capacity, this influence, if present at all, was scarcely noticeable.

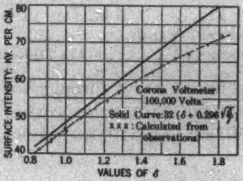


FIG. 5 — COMPARISON OF VOLTAGE AS INDICATED BY READING ON TERTIARY COIL WITH CALCULATED VALUES AT DIFFERENT DENSITIES OF AIR

The above results, therefore, with the larger instrument are not to be considered as an attempt at calibration. They show rather, that in applying a range of voltage and pressure to the instrument to test its value, a method which has been commonly relied on for indicating high-tension voltages in transformers is revealed as subject to large error. In fact, the observations as taken constitute a conspicuous example of the value of the corona voltmeter in checking the ratio of transformation between the tertiary coil and the high-tension winding of a transformer. The only open question is the accuracy of formula (**1**), and this formula, both as to the value of its constants, and the form in which the values are related, is agreed upon with only slight divergence among many experimenters.

Aside from all question of the accuracy of the above deductions the instrument has been carried through a range of voltage between 50,000 and 100,000 volts. Particular values of voltage as indicated by the instrument on the low-tension side, and by the appearance of corona, may be repeated as often as desired within a fraction of one per cent. If a suitable method of calibration can be devised, a calibration curve between the voltage and pressure may be drawn giving an absolute calibration of the instrument in terms of pressure and temperature.

METHOD OF MEASUREMENT OF VOLTAGE

The instrument is susceptible of usage in two ways. (1) It may be set for a given voltage and the applied voltage gradually raised until the desired value is reached, as indicated by the instrument, or (2) with an unknown voltage applied to the terminals, the pressure in the tube may be gradually lowered until corona appears.

The first of these methods would be that commonly used in the testing of insulation. In applying this method the necessary operations are as follows: Read the temperature in the corona tube, take from a table or curve, calculated from the dimensions of the instrument, the value of pressure which, with the observed temperature, corresponds to the voltage required. Adjust the pressure to this value by means of a hand pressure and vacuum pump. Gradually raise the voltage from some lower value until the presence of corona is indicated by one of the methods already described.

Table V gives the values of pressure for the 50,000-volt instrument for voltages between 20,000 and 50,000 at temperatures between 10 deg. and 30 deg. cent. The values have been calculated as follows:

The inner tube having a diameter 9.51 cm., and the central rod a diameter of 0.396 cm., it may readily be shown that for a difference of potential V between the central conductor and the outer tube, the electric intensity at the surface of the central conductor is $1.593\ V$. The critical corona forming surface intensity as calculated is $32\,(\delta + 0.665\,\sqrt{\delta})$. Equating the two expressions and giving V any desired value, we obtain corresponding values of δ. Formula (2) gives the value of δ. Since p is the pressure in centimeters of mercury and t is the temperature in centigrade degrees, we at once obtain for any observed temperature, a pressure to which the tube may be adjusted in order to show corona at the particular voltage V for which p has been calculated. Obviously a series of curves can be drawn to take the place of the table if desired.

TABLE V.

PRESSURES IN CM. MERCURY, AT WHICH 50,000-VOLT CORONA VOLTMETER MUST BE SET TO INDICATE VARIOUS VALUES OF VOLTAGE AT DIFFERENT TEMPERATURES

Max. volts	Temperature, degrees centigrade																
	10°	15°	16°	17°	18°	19°	20°	21°	22°	23°	24°	25°	26°	27°	28°	29°	30°
20,000	37.2	37.8	38.0	38.1	38.2	38.4	38.5	38.6	38.7	38.9	39.0	39.2	39.3	39.4	39.5	39.7	39.8
25,000	49.8	50.7	50.9	51.0	51.2	51.4	51.6	51.8	52.0	52.1	52.3	52.5	52.7	52.8	53.0	53.2	53.3
30,000	63.0	64.2	64.4	64.6	64.8	65.1	65.3	65.5	65.7	66.0	66.2	66.4	66.7	66.8	67.1	67.3	67.5
35,000	76.2	77.5	77.8	78.0	78.3	78.6	78.9	79.2	79.4	79.7	80.0	80.2	80.5	80.8	81.0	81.3	81.6
40,000	90.3	91.9	92.2	92.6	92.8	93.2	93.5	93.8	94.2	94.5	94.8	95.1	95.4	95.7	96.0	96.4	96.7
45,000	103.8	105.7	106.0	106.4	106.8	107.2	107.5	107.9	108.2	108.7	109.0	109.3	109.7	110.0	110.4	110.8	111.2
50,000	118.1	120.2	120.6	121.0	121.4	121.9	122.3	122.8	123.2	123.6	124.0	124.4	124.8	125.2	125.6	126.0	126.5

In the second method mentioned, in which it is desired to measure the value of an unknown voltage, it is only necessary to run the pressure in the tube up to a value corresponding to a voltage known to be above that to be measured. The pressure may then be lowered rapidly by allowing the air to escape until corona appears. Having approximated the voltage by this means the pressure may be raised again above the value at which corona appears and then lowered as gradually as desirable in order to establish any particular degree of accuracy of observation. The table of pressures as described above may also be used in this case. In using this method it is inadvisable to lower the pressure by any considerable amount below the corona forming pressure. If this is done the volume of corona increases greatly, which may result in spark-over, and which if allowed to continue will make it necessary to clean the surface of the central conductor.

Pressures may be read if necessary on an ordinary mercury gage. If this is done it is also necessary to read the actual value of the atmospheric pressure. However, pressure gages are available which read absolute pressure directly, thus obviating the necessity of making the additional observation of atmospheric pressure.

PERMANENCE OF CALIBRATION

It is well known that the condition of the surface of the central conductor as regards inequalities has an important bearing on the sharpness with which corona will appear. Small specks of dirt cause regions of high electric intensity which form sparks or point discharges at voltages below that corresponding to corona for the smooth conductor. In the use of the instrument as described, therefore, it is important that the central conductor should be carefully cleaned before insertion into the outer tube.

No special difficulty is met in so cleaning the surface of the wire that no preliminary sparks appear and so that the appearance of corona is not only sharply marked but may be repeated many times without a variation in the value of the corresponding voltage.

Time Tests. In order to test the possibility of the repetition of the readings, a series of observations were taken on a voltmeter differing somewhat from those described, extending over a period of five months. This voltmeter was open to the air and subjected only to atmospheric variations of the density.

Readings of the corona voltage were taken four or five times a week throughout the period, and showed when corrected for temperature and pressure a maximum deviation of six-tenths of one per cent from the calculated value. In this series of observations the wire was cleaned every day or two.

Permanence of Surface. In order to determine whether, and to what extent, the surface of the wire deteriorates with use, a number of tests were conducted on brass, nickel, and silver plated rods in addition to copper and steel rods commonly used. These tests consisted of the running of the instrument continuously with voltage slightly above the corona forming voltage, interrupting the run at intervals to see to what extent if any, the observed corona voltage had been lowered. One per cent excess voltage will result in a well formed corona, while five per cent excess gives one of marked volume and sound. The results were as follows:

Brass rod, 0.234 cm. diameter, primary voltage at start 61.2; run for 44 minutes at one per cent excess voltage with a number of intermediate readings. Corona voltage at end of test 61 volts, a change of about one-third of one per cent.

Nickel plated rod, 0.24 cm. diameter, voltage at start 61.5, run for 48 minutes, at one per cent excess voltage with intermediate readings, voltage at end 61.1 volts a decrease of less than two-thirds of one per cent.

Silver plated rod, 0.24 cm. diameter, corona voltage at start 61.5, run for 42 minutes and from one to 5 per cent excess voltage, with intermediate readings; corona voltage at end of test 61.5 volts, thus showing no deterioration.

The lowering of corona-forming voltage in the first two of these wires is in a great measure accounted for by the elevation in temperature in the tube due to the presence of corona and is not all due to deterioration of the surface. Thus in the case of the brass wire the temperature rose during the test from 23.9 to 25.2 deg. In the case of the nickel rod the temperature rose from 25.4 to 26.5 deg. In the case of the silver rod the rise in temperature was only from 26.9 to 27.3 deg. The conclusion from these tests therefore, is that the life of any polished conductor for the purpose of observing corona should be quite long for any material which does not oxidize freely in the air.

It is quite obvious that the design of the corona voltmeter as already described, permits the ready removal of the central conductor in case it should be suspected that the surface is not clean. The use of the telephone as a detector indicates very promptly the presence of any single points of discharge, such points having a characteristic sound in the telephone which is quite different and of a very much lower intensity than that corresponding to full corona.

DIMENSIONS

The dimensions of the corona voltmeter are apparently determined by three factors; the diameter of the corona tube, the length of this tube, and the requirements of insulation of the connection to the central conductor where it passes through the ends of the outer or pressure cylinder.

The diameter of the corona tube is largely determined by the maximum voltage. It has a simple well-known relation to the diameter of the inside conductor for any particular value of corona forming voltage. The most advantageous relation of these two diameters has not yet been determined. For example, no direct study has been made of the increase that is possible in the diameter of the central conductor before the formation of corona is coincident with that of spark-over. For smaller sizes of conductor it is possible to raise the voltage by considerable amount above that at which corona starts without resulting spark-over. With increasing diameter of conductor, however, this possible range above corona voltage becomes narrower. From a number of indirect observations, the present experiments seem to indicate that a ratio of diameters of the inner conductor to outer cylinder greater than 0.1 is apt to be attended by spark-over. These observations have largely determined the sizes of central conductor which have been used in the two instruments described above.

The length of the interior or corona cylinder may be considerably less in each case than those adopted in the two types of instrument as described. In order to determine the length absolutely necessary a number of experiments have been made on tubes of the same diameter but of varying lengths, under atmospheric conditions. With tubes 6.35 cm. in diameter and rods 0.317 cm. in diameter, observations of corona voltage were made with tubes of lengths four, two, one and five tenths, and one diameters in length. The observations show that with decreasing length there was no perceptible rise in the corona voltage until two diameters of length was reached. For this length there was an apparent rise in the corona voltage of about one-half of one per cent; for one and one-half diameters a rise of about one per cent, and for one diameter of length corona voltage was about three per cent higher than for tubes of lengths four or more diameters.

It should be noted, however, that the use of the galvanometer as the indicating instrument requires a longer inner tube in order to make available a sufficient amount of ionization for the deflection of an instrument of ordinary sensitivity. There are obvious advantages in the use of a galvanometer, and it is our opinion that on this account it is not advisable to attempt a corona tube shorter than three diameters.

The requirements of insulation of the leading-in conductors add the greatest proportion to the length required for the whole instrument. The conditions here are much the same as at the leading-in terminal bushings of a transformer. The inner end of such a bushing can be brought fairly close to the inside cylinder but must not disturb the distribution of the electric field within that cylinder nor introduce any regions of higher intensity outside the cylinder.

The observations on the two instruments as described indicate that it would not be possible to reduce the dimensions of the smaller type without limiting its range. The larger type, however, is unnecessarily large in every direction. The outer cylinder can be reduced somewhat in diameter as can also its length without modification of the interior corona cylinder and central conductor. The interior cylinder can also be reduced somewhat in length without seriously inpairing the accuracy of the reading of the indicating instrument. Apparently it should be possible to construct a corona voltmeter for 100,000 volts with an over all length of about two meters and a maximum outside diameter of 45 to 50 cm.

The question of the extreme reduction of the dimensions of instrument as well as that of direct calibration, can only be determined by further investigation. It is the hope of the authors to carry forward such investigations. The present paper has as its principal object to show that it is possible to construct and operate a voltmeter based on the corona principle, which possesses an absolute calibration, a wide range, a high degree of constancy, and several other advantages over existing instruments for the reading of high voltage. Thanks are extended to Dr. W. B. Kouwenhoven and Mr. W. S. Brown for their assistance with the oscillograms and in other particulars throughout the work.

SUMMARY

The following conclusions seem to be justified by the experiments which have been described:

1. An instrument making use of the appearance of corona as an indication of the maximum value of alternating voltage has been devised and constructed in two sizes for ranges 20,000 to 50,000 volts and 40,000 to 100,000 volts respectively.

2. The principle of operation depends on a natural constant and the calibration of the instrument is definitely determined by its dimensions. This calibration may be supplemented by calibration with any existing standards.

3. In setting for different voltages no alterations in dimensions nor other manipulation is necessary. Variations in setting require changes in air pressure only. The necessary changes may be effected with a hand pump.

4. Three, and if necessary, four means of observing the indications of the instrument are described. They may be used simultaneously, thus serving as checks upon each other.

5. No spark-over, nor arc, nor energy consumption occurs in the operation of the instrument.

6. No series resistance nor condensers are necessary to its operation.

7. Observations may be repeated rapidly and any number may be taken with one setting.

8. The calibration is within wide limits, independent of wave form and frequency. It is also independent of electrostatic influence of neighboring conductors and objects.

9. It is readily constructed in portable form.

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BIBLIOGRAPHY

1. J. B. Whitehead, Trans., A. I. E. E., XXIX-XXXV, 1910-1915.
2. H. J. Ryan, Trans., A. I. E. E., XXIII, 101, 1904.
3. F. W. Peek, Jr., Trans., A. I. E. E., XXXI, 1051, 1912.
   J. S. Townsend, *Electrician*, 71, p. 348, 1913.
4. W. Weicker, *Elek. Zeits*, XXXII, 436, 460, 1911.
5. F. W. Peek, Jr., Trans. A. I. E. E., XXXIII, II, 1721, 1914.
6. Alex. Russell, *Proc. Phys. Soc.* XXIV, I, 1911.
   Alex. Russell, *Phil Mag.*, 6 Vol, II, 258, 1906.
7. de Kowalski & Rappel, *Phil. Mag.*, 1909.
8. L. W. Chubb, Trans. A. I. E. E., XXXV, 1916.
9. Sharp & Doyle, Trans. A. I. E. E., XXXV, 1916.

DISCUSSION ON "THE CORONA VOLTMETER" (WHITEHEAD-PULLEN), CLEVELAND, OHIO, JUNE 29, 1916. (SEE PROCEEDINGS FOR JUNE, 1916.)

L. W. Chubb: Dr. Whitehead's paper brings before us a new standard voltmeter which I think, if all the irregularities can be taken out of it, should displace the sphere gap as the primary standard. There is some doubt as to the practicability of the scheme for a working or secondary standard.

In the earlier papers Dr. Whitehead has given us an idea of the sharp indications of the appearence of corona and his Table I in the present paper certainly is an exhibit of remarkable observations by three different methods; and we are to understand that the fourth method also checks equally well. The structure has a great advantage over the sphere gap, in that it is independent of extraneous objects. Dirt specks, oil, etc., to a certain extent, affect both types of meters but the enclosed wire is less apt to have dirt settle on it.

Several other schemes for crest voltmeters have been described in the TRANSACTIONS and I have had experience with all of them, including the Ryan type of corona voltmeter. One of the old students of Prof. Ryan set up a cone-shaped corona voltmeter in the laboratory several years ago, and tests showed that the indication of transients was its greatest advantage. When a surge in voltage would come, you could see the corona shoot toward the large diameter end of the cone. As a practical instrument, however, and for indications of steady voltage it did not seem to be a success. In all our experience, the scheme which was reported in my paper at the midwinter convention last February, we still believe is the most practical and the best for all around testing.

I would like to ask Dr. Whitehead a few questions in regard to the paper. In the first place he speaks of not having an absolute method of calibration, and points out that the value of the instrument depends upon a calibration, which can be accepted universally. At the present time the calibration depends upon an empirical formula for the electric strength of air. I believe if the method of calibration is used, that was presented in our 1913 paper, the author will obtain great satisfaction, because it is an absolute method which works from the high-tension side and depends only on a current or potential standard and the physical dimensions of a guard-ring air-condenser.

The crest-factor calculations in the paper are carried out too far. I have found that it is very hard to calculate crest factors accurately with small amplitude oscillograms, and unless a voltage measuring method is used which derives voltage from the high-tension winding and corrects for the crest factor, there may be an appreciable error.

I was surprised at the inaccuracy of the tertiary coil in the tests. It was more than is usually to be expected and the difference between tertiary voltage and calculated voltage should have been checked by tests with parallel variable-load reactance. I would ask whether humidity has any effect on the results and whether there is any appreciable error in reading the air temperature inside of the tube It seems to me that the adiabatic expansion and compression, due to rapid change in pressure, will cause temperature changes which cannot be followed by a sluggish thermometer. I would suggest that a test be made to measure the same voltage, first by holding the voltage constant and letting out the air, then by holding the pressure constant and raising the voltage.

I would ask whether improper centering and vibration of the wire will affect the calibration, and whether the author would expect two voltmeters built to the same specifications with the usual workshop precision, to check accurately

Clayton H. Sharp: It seems clear to me that Dr. Whitehead has given us a splendid instrument, which, although the exact value of the constant may not be known, is superior to anything we have now for the purpose of standardizing high-voltage measurements. It may not make an everyday working instrument, perhaps for the same reason that the Siemens electrodynamometer is not a good working instrument; that is, that it requires an extra manipulation to give a reading, namely an adjustment of the pressure of the air. Hence it is not so quick as a direct-reading instrument might be, but as a standard instrument it seems to leave little to be desired, when once the correct value of the constant in the equation has been determined.

James R. Craighead; We should give Dr. Whitehead credit for the procedure he pursued in the development of this instrument. It was, in the first place, simply an instrument used in air, and without special standardization of conditions other than the exact dimensions of the physical apparatus. In its present form, it shows a degree of accuracy which should be amply satisfactory for its use as a standard, and the reason for that accuracy is the fact that the conditions have been so carefully controlled.

One further point—as soon as you inclose a high-voltage conductor and have corona develop, there is an ionization of the air, which is used as an indication of the actual development of corona. On some instruments of a somewhat similar character, I have observed that a certain amount of that ionization remains for a considerable period of time in the enclosed air, and I should like to ask Dr. Whitehead whether he has any difficulty in repeating immediately and frequently successive observations within this enclosed chamber without any device for ventilating in order to produce air that is free from ionization.

The point that Mr. Chubb mentioned in regard to the change of temperature that is associated with change of pressure, seems to me to be especially important. If we are to measure a voltage by the use of an air pressure, we are going to pump air at a definite temperature into a cylinder, and then a change of temperature will be going on within the cylinder to some extent as the pressure diminishes, and an accurate record of the temperature at the moment when the corona appears might be diffcult to obtain.

C. Francis Harding: The paper presented by Dr. Whitehead marks another signal advance toward the much desired primary standard for high-voltage measurement to supersede the needle and sphere spark gaps.

In analyzing this problem of the measurement of high voltages care should be exercised not to confuse methods suitable for fairly accurate practical measurements, with the requirements of a primary standard of voltage. A primary standard, if I understand the term aright, should be based upon fundamental laws, a knowledge of which, together with the constants of design of the apparatus will enable such a primary standard voltage to be reproduced under any local conditions which may exist. This is not possible with the needle spark gap and there is probably some error in the hypothesis and therefore in the values of calculated voltages for the sphere gap. Several investigators have pointed out the rather large errors possible, due to varying local conditions such as foreign matter upon the spheres, distorted electrostatic field between spheres, effects of varying air pressure, temperature, humidity, frequency, etc. Furthermore the present dual standard of needle and sphere gaps for use below and above 50 kv. respectively is particularly objectionable since the two standards can not readily be made to coincide at the transition point where both should be correct. Such a method gives only an instantaneous indication of the voltage and the measurement itself, by means of the spark-over, is quite likely to disturb the circuit to such an extent as to prevent the maintenance of the desired voltage in the circuit, not to mention the impossibility of a permanent indication of the same. Both spark-over methods, although valuable for practical tests are unsuited for use as permanent primary standards.

The application of a definite ratio of transformation either from a constant-potential transformer or from a voltmeter coil of a high-voltage transformer to the present primary standard of voltage has apparently been used for practical measurements with considerable accuracy. I do not see that one can ever hope to use it however as a high-voltage standard, since it is dependent upon the condition that this coil inclose the average flux of the secondary coils under all conditions of load and power factor. While this condition may be closely approximated by carefully locating the voltmeter coil, one would not feel safe in predetermining such a ratio from design data. There is no way to prove that such a calculation is accurate save by the spark gaps, and the latter have been in turn based upon the ratio method in the first place. In the paper under discussion considerable error has been reported for one particular placing of the coil. The speaker has found it necessary, in the determination of corona losses upon transmission lines, where the voltmeter coil was used as a convenient intermediate agent, to plot calibration curves between standard volts determined by the present sphere-gap standard, and voltmeter coil readings for each change of secondary connections. For example, the addition of 800 feet of No. 4 B & S transmission line with a 12-foot spacing will offer sufficient capacity at 180 kv. to cause the actual ratio curve to depart 8 per cent from the straight line calculated from the constant ratio which is accurate at lower voltages. In this transformer the voltmeter coil is made up in two parts, each of diameter of the average secondary coil and so placed as to inclose as nearly as can be predetermined the average flux of the secondary. This error is about the same as that reported by Dr. Whitehead for the voltage coil method with the capacity of the 100-kv. corona voltmeter in circuit.

In looking further for possible primary voltage standards it would seem logical to investigate the possibilities of making use of the force action in a uniform electrostatic field just as our low-voltage instruments make use of uniform electromagnetic fields. The former are quite as readily produced at high voltage as are the latter at low voltages.

In a written discussion of the paper on "Crest Voltmeters", the speaker outlined briefly some work by Messrs. Phelps, Wright and Holman carried on during the last two years at Purdue University upon the use of force action between parallel plates at high voltages, in which the theoretical calculated constant ratio between voltage and distance between plates for a constant force action was very closely checked in actual tests. This apparatus, constructed upon the principle of the Kelvin attracted disc electrometer, may have some possibilities as a primary standard for high voltages, although not suitable for use in a portable secondary voltmeter.

Another investigator, Mr. L. L. Bouton, also of Purdue University, has this year shown conclusively that there is little of value to be expected from an instrument based upon the attraction between metal spheres of large size, for, although test values can be reproduced more readily and are probably less influenced by local conditions than the spark gap, yet accurate theoretical determination of the field and the resulting force action between spheres is very difficult when the diameters of the spheres are large with respect to the distance between their centers.

The paper under discussion presents another apparently very fertile field for the study of possible high-voltage standards. Although many factors are involved which should and probably can be readily held constant in such an instrument, this apparatus has the advantage of several check readings for determining the critical voltage. It would seem also that if the dielectric strength of air under specified conditions were standardized, that this method of determining voltages would be entirely reproducible.

I wish to emphasize as forcibly as I may, the importance of the early study of this problem of high-voltage standards by the proper committee of the Institute. The use of high voltages has become so general that we must have something more definite to use as a reference, a standard which may be reproduced at any time with any local conditions, guaranteeing a test voltage determined by the use of proper constants calculated from the dimensions of the apparatus involved and the fundamental laws of the electric and magnetic circuits.

F. W. Peek, Jr.: I have heard a great many arguments for and against the various methods of measuring high voltages. It is generally a question of which method is most convenient and most adaptable to any given investigation. All of the methods discussed have their advantages and disadvantages. In investigating high voltages of extremely short duration, durations in the order of a millionth of a second, I have found the sphere gap necessary. When the sphere gap is properly used, it is not difficult to use it in that way, it will measure correctly a-c. voltages, d-c. voltages, and transient or lightning voltages. I will not say more about the measurement of transient voltages here, but will refer you to my paper read in San Francisco, September 1915. This paper also gives the characteristics of transient corona produced by voltages lasting only one-millionth of a second; it is possible to see this corona and to detect whether the wire is positive or negative.

Jacob Kunz: It is possible to add still another instrument to measure d-c. or a-c. voltages. Dr. Whitehead has used the electroscope, the galvanometer, and the telephone. It is possible still to add to those corona-measuring devices an instrument which directly indicates pressure, because as soon as the corona starts, either d-c. or a-c. corona, the pressure increases noticeably and measureably. It is very easy in the case of air with voltages only as high as 10,000 volts to get an instantaneous increase of the pressure to say 3 cm. of mercury. This new voltmeter, which is based on the increase of the pressure due to the corona itself, is very accurate, and we have found recently you can use this increase of pressure by means of an aneroid barometer to measure voltage or current; the positive corona current, at least being proportional to the increase of the pressure, so that by an aneroid barometer, one can also measure currents and potential differences.

This brings out a precaution which has been taken in this instrument of Dr. Whitehead's, namely, that it uses change of pressure in order to find the starting point of the corona, but when the corona starts, then the corona itself changes its pressure. There is a reaction of the pressure, as the corona increases the pressure itself increases, and if you keep the corona going, in a little while heat will be developed, which has to be taken into account also.

Concerning the constants of the formulas—we have thirty-two in the formula of Whitehead, and a different constant in the formula of Peek.

I think a careful investigation should be made into these constants, because Farwell found that these characteristic constants in the corona are distinctly different for positive and negative corona.

Then it has just been mentioned, that the a-c. corona for high frequency is different from the a-c. corona for low frequency, or d-c. corona; indeed, you can make experiments, and if you use d-c. corona and introduce only a little spark gap of a mm., or half a mm., then the visual phenomenon of the corona is entirely changed and the characteristics also are very much changed. So far as I understand Townsend and Watson, they always used spark gaps in connection with the corona, and through these spark gaps the nature of the visual corona is entirely changed; for instance, in a d-c. corona with the spark gap, the positive wire is surrounded by a uniform glow and the rest of the tube is dark. If a spark gap is introduced, however, the whole corona is filled with streams of light, which are separated from each other, and in some cases they are very uniform and the whole tube glows uniformly.

Corona assumes quite a different character, for instance, in the case of hydrogen. Experiments have been made in our laboratory on corona in hydrogen and other gases, and the characteristics between positive and negative corona are entirely different. They do not resemble each other—one is a continuous and the other is a discontinuous corona, and the negative corona appears in the form of beads, while the positive corona is uniform. In this case, the difference between positive and negative corona in hydrogen, is so great that the hydrogen corona tube can be used as a rectifier. We have been able to rectify voltages up to 10,000, and there is no reason why we should not be able to rectify 100,000 volts.

John B. Taylor: Can the method of determining corona formation by listening for sound in a telephone receiver be used when working with continuous voltage?

F. W. Peek Jr.: Some years ago we rectified by corona in air. A full description of this is given in an Institute discussion.

J. B. Whitehead: I think all of the speakers have agreed that our instrument has some promise as a standard. That was our chief object. Our feeling is also quite pronounced that it will also be a working standard, but we are quite satisfied at this time to find such a unanimity of feeling that there is here the possibility, at least, of an ultimate standard of high voltage.

As to the cone shaped wire mentioned first by Mr. Chubb and last by Dr. Lloyd. The cone shaped wire, in giving the direct scale, has this one difficulty—that the presence of corona causes a slight elevation of temperature. This slight elevation of temperature means that corona will appear at a lower voltage, so, consequently, if you use the cone shaped wire, even supposing you hit the actual voltage immediately by seeing the point along the length of the wire at which it comes out, that position will change almost at once. Corona on a vertical wire, is often seen to walk up the wire, owing to this cause, hence the difficulty of securing anything like permanence in the graded diameter.

As to the determination of peak factors, the general conditions under which our oscillograms were taken are described in the paper. A third decimal place has slipped in, as a result of taking an average of several values. I agree with Mr. Chubb that it is not possible to measure peak factors to the third decimal place. However, the gradual variation of the peak factor as described in the paper was quite obvious in our determinations, taken over a wide range. The comment is quite proper. The weakest point in the determination of maximum value readings of voltage from the low-tension side, is the oscillogram.

The transformer which we used was constructed before the engineers who are interested in the possibilities of the tertiary coil were quite as certain as to the accuracy attainable, as they are now. Having consulted them, they agree that the design of the transformer that we have, as regards the tertiary coil, could be greatly improved. My comments on that point are not intended in any sense to depreciate the present day value of the tertiary coil, as a means of measurement.

As regards the humidity inside of the tube, if you allow the air in a corona tube to expand very rapidly through an orifice, you will undoubtedly get cooling as you will everywhere in the rapid expansion of air, and you will also have condensation of moisture. In our experiments, this matter is readily taken care of by providing a large opening for the air and letting it out so slowly that you do not get appreciable cooling and condensation. By providing large enough openings, the air can be changed very readily, and you can get as uniform a distribution of temperature as you please. The temperature is measured with a thermometer inside. So far as we have been able to observe we have not found any indications that this is a serious difficulty—indeed, we have not observed it as a difficulty at all, we have never found anything other than a slow change of one or two degrees throughout the course of a full run.

The centering of the wire is purely a mechanical process. We have suitable templates for the inner tube of the voltmeter, as shown in the diagram, and these templates can be adjusted through the side hole which is large enough to get your hand in, and by looking into the side hole at right angles and shifting the template, it is easy to determine the centering. The final centering is done in the instruments we described at the ends. The holes through the insulators are large enough to give us quite three or four mm. in any direction, and this is found to meet the situation.

Mr. Craighead raises the question about ionization. Some of my earlier experiments convinced me at least, although not every one, that the normal ionization in the air has no effect on the beginning of corona. These experiments included the location of radio-active substances in the neighborhood, illuminating the wire for ultra-violet light, and other well known sources of ionization, so that there was no lowering of corona voltage.

On opening the corona voltmeter after prolonged use, there is very decided evidence of ozone. We have never been able to detect, however, any variation from the calculated values of corona.

With reference to Prof. Kunz's very interesting description of the use of the elevation of pressure as corona detector I hope he will present the results of his studies in that direction, so that we may have a complete account of them. I would like to call attention, however, to the fact that in the use of the corona voltmeter by which we read pressures to one-quarter of an mm.,—of course, we could read them more closely, but that is quite sufficient to give an accuracy of less than one-half per cent—we have never detected any increase in pressure due to the presence of corona. That does not mean Prof. Kunz has not found the increase of pressure, but we are working on the threshold appearance of corona where the increase of pressure is very small. It is very small because we have quite a large volume of air in the corona voltmeter, and it is only the initial appearance of corona; consequently there is a generation of but very few ions, considered with reference to the number of molecules in the whole volume of the system. The use of elevation of pressure as the result of corona would seem to me to be subject to this very limitation that he speaks of in the resulting temperature. Certainly we have found that if we carry the voltage above the corona-forming voltage, five or ten per cent above, so as to get a large corona, changes in temperature are immediately obvious, and consequently they would introduce error.

Prof. Kunz, I am sure, will be interested to hear that we have carried out some d-c. experiments during the past year, in which we have been able to get negative corona without the appearance of beads, and I believe that the negative corona without the appearance of the beads and localized spots is simply a question of constancy of circuit conditions and of clean surface. That is our conclusion. If you allow negative corona to remain any time, after awhile it will form into these beads, but there is no doubt that negative corona can be obtained without the localized sparks.

As to Mr. Taylor's question—the sound given out by the corona is not the note corresponding to the frequency of the circuit, it is entirely due, in my opinion, to indiscriminate snapping sparks over the minute irregularities of the surface of the wire, irregularities which cannot be gotten rid of, although we polish it to a very high degree. Therefore, although we have not before us, the account of our experiments on the sound of d-c. corona, I feel sure that the sound could be used there also.

Since the experiments reported in the paper, we have compared the corona voltmeter with the sphere-gap, as shown by Fig. 1. The upper solid curve is the calculated corona curve, using the formula of my work, namely 32, for the first constant, or 0.518 for the second. The long dash upper line is the curve of corona voltage as taken from Mr. Peek's formula, namely, 31 for the first, and the second constant is 0.54. The curves are plotted between kilovolts per centimeter at the surface of the wire, and the range of atmospheric change, affecting the whole range of the abscissa, is 10 or 15 cm. below atmosphere, to 45 or 50 cm. above atmosphere, so that this is a rather wide range of air density, and therefore the difference between Mr. Peek's constant and my own appears somewhat intensified.

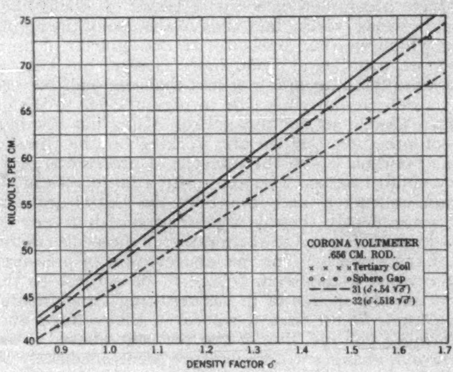

FIG. 1

Now, then, the lowest curve with the cross marks gives the observations on the tertiary coil of the transformer,

The tables shown in the paper give the accuracy with which the low-tension reading can be repeated, and the circles with the dots represent the sphere gap readings, all these measurements being taken on a 12.5-cm. sphere gap. The readings were taken as follows: We would set the pressure and gradually raise the voltage until corona appeared with the spark gap in parallel with the corona tube, set to a value which we knew was too great for spark-over. Keeping the pressure in the tube constant we would repeat over and over again the corona observation, closing the sphere gap by 1/100 mm. each time. Finally we came to a voltage value in which the sphere gap would let go just before we had the corona.

The interesting point about the curve, it seems to me, is that it shows that the calibration of the spark gap and Mr. Peek's corona values, are of course, coincident because they are based on the same standards and methods of measurement. The falling of the tertiary coil observations below these is entirely due to the construction of the tertiary coil. The variation of the spark-gap determination from the calculated curve would not ordinarily be considered great. I call attention to the irregularities of the gap readings as compared with those of the corona, as referred to their respective curves.

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THEORY OF PARALLEL GROUNDED WIRES AND PRODUCTION OF HIGH FREQUENCIES IN TRANSMISSION LINES

BY E. E. F. CREIGHTON

ABSTRACT OF PAPER

The overhead grounded wire is used for three purposes: lightning protection, mechanical support for towers, and a test circuit. The functions of the grounded wire are subdivided into at least four categories: First, the vertical grounded wire; second, the lightning rod extending above the ground; third the electrostatic induction in the horizontally situated wires, and fourth, electromagnetic induction.

The vertical wire prevents splitting of the poles. The lightning rod is of mooted desirability. The electrostatic induction for a given cloud on wires under various conditions is worked out in this paper. There is given also the protective values of overhead grounded wires in different positions and in different numbers. The effects of electromagnetic inductions have been taken into account. Theory is given to show that the grounded wire introduces into the main wave of induced lightning surge a superposed high frequency of electromagnetic induction.

The several factors to be taken into account in the process of determining the protective value of a grounded wire are as follows:

1. Strength of electric field in the neighborhood of the line wires.
2. The direction of the gathering charge in the cloud, that is the path of the discharge relative to the line, parallel or perpendicular to the line before it turns vertically downward to the earth.
3. The screening effect obtained by the use of several wires, with and without grounded wires.
4. The initial momentary potential induced on a wire at the instant the cloud discharges to earth.
5. An instant after the lightning discharge has taken place, the sudden increase in capacitance between the power wire and the adjacent parallel grounded wire.
6. The effect of the number and location of parallel grounded wires.
7. The effect of electromagnetic induction between the horizontal part of the grounded wire and the parallel power wires, in which the energy of the lightning charge on the grounded wire is more or less transferred to the power wire, instead of being dissipated in the earth. High frequencies are produced in this transformation.
8. The gradual transference of the charge which travels along the power wire to the successive sections of the grounded wire and its dissipation in the earth.

A cloud charge is chosen of such value as to produce corona potential on a No. 000 B. & S. wire, strung at a height of 1000 cm. (33 ft.) above the surface of the earth. This storm cloud is used as a standard in all cases for comparison. The induced voltage on any wire by lightning is directly proportional to the height of the wire above the earth. The induced quantity is not quite proportional due to the variations in the capacitance of the wire at different heights. For heights between 30 and 60 ft. (9.1 and 18.2 m.), however the quantity can be considered as approximately proportional to the height.

The quantity induced on the wire is only slightly affected by the diameter of the wire. This leads to the conclusion that a small grounded wire is nearly as effective as a more expensive large one.

The theory is given to show that even on a non-grounded circuit a charge can be induced by a cloud and produce practically the same potentials as when the circuit is grounded. The only exception is that of circuits of short length.

The instantaneous value of induced potential on a circuit is independent of the number of wires used. Using a greater number of wires reduces the quantity per wire but does not decrease the instantaneous value of the potential at the instant the cloud discharges to earth. Even the grounded wire may take the full potential and give no relief at the first instant. Whether it does or not depends upon how quickly the discharge takes place from cloud to earth, and how frequently along the line the grounded wire is earthed. There is, however, a screening of electrical energy by increasing the number of power wires. In other words, each surge has less energy although it has not initially less potential.

There is given a table of the reduction of quantity per wire as the wires increase in number from one to seven.

The two factors in the electrostatic protection of the overhead grounded wire are screening and increase of capacitance of line wires. The presence of the grounded wire reduces the quantity induced on each of the power wires and incidentally after the cloud discharges to earth the grounded wire takes over part of the charge from the power wires and in taking it the capacitance of each power wire is increased. Therefore, with the same quantity of electricity the potential is reduced by this increase in capacitance.

The protection afforded by one parallel grounded wire can be expressed as a very simple equation. The protection for each power wire can be calculated entirely independent of how many there are.

The general equation to express the protection afforded by two parallel grounded wires is more complex but if the two grounded wires are placed far apart their protective values can, with only a small error, be calculated independently.

As the charge runs to earth on the grounded wire at the instant the cloud discharges, it induces on the line wire by electromagnetic induction a considerable voltage in the usual conditions of the overhead grounded wire with low resistance in the earth connections and from which part of the protection afforded by the grounded wire is lost by the fact that the energy oscillates in the ground circuit and is transferred to the power wire.

The natural frequency of this wave train is found by multiplying 183,000 miles (300,000 km.) per second by the number of earth connections per mile of grounded wire. The frequency is usually over a million cycles per second.

Traveling waves are more or less absorbed as they pass each successive loop of the grounded wire, according to the value of the resistance of earth connection. In any case an endeavor should be made to have the resistance in the earth connection somewhere near the critical damping value. This prevents initial oscillations in the ground circuit and also increases the rate of absorption of a traveling wave.

A slight amount of high frequency is produced in a circuit by transposition of power wires. This may be of the order of 2 per cent to 5 per cent of the main voltage.

The general deductions for practical use taken from the theory given are as follows: From a theoretical standpoint a single grounded wire should be placed as near as practicable to the power wire in order to get the greatest electrostatic protection. The grounded wires are a little more effective when placed above a power wire than when placed below it.

In installing overhead grounded wires the greatest advantage can be obtained by keeping the overhead grounded wires as far apart as possible, that is to say, installed, as far as practicable on opposite sides of the power wires. The protective value of the second wire will then have its full maximum possible value. Also from the electromagnetic standpoint, the two wires should be placed, so far as practicable, on opposite sides of a power wire in order to reduce to a minimum the transfer of surge energy to the power wire.

The most practicable condition of protection by four grounded wires is to use the four wires in a rectangular formation which gives the widest separation. Naturally two will be above the power wires and the other two will be either below or at each side about on a level with the two lowest power wires. The mechanical conditions of installation will dictate where these wires will be hung and it is necessary to follow the rule to make the distances between the several grounded wires as great as the conditions will permit and still keep the grounded wires as near a power wire as safe mechanical clearance will justify.

I—Introduction

THE OBJECT of this paper is several-fold; primarily it is an endeavor to place the practise of the use of overhead grounded wires on a firmer engineering footing and to discuss the conditions of line construction which cause and suppress high-frequency surges. The desire is to present the material so that the conditions of installation may be made to give the greatest degree of protection with a minimum of undesirable reaction and lowest cost.

In the mathematical analysis there is no so-called higher mathematics. The difficulties involved are due simply to the extremely long simultaneous algebraic equations. It is a matter of labor more than skill. The basis of this analytical work was given by Maxwell, Kelvin and Heavyside and their familiar notation is used. Since most engineers of power systems are too occupied with other problems to juggle involved logarithmic equations, all this analysis is separated from the main body of the paper and is given only as a means of checking up the writer's conclusions. In most cases the analysis of the value of a grounded wire reduces to very simple formulas, due to the cancellation of many factors in the long, involved equations.

Many operating engineers have noted high potentials across choke coils of low inductance and other phenomena, which point directly to the presence of extremely high frequencies in traveling waves on the line. An endeavor has been made to analyze the possible sources of high frequency. There are at least four of these sources.

The earliest use of the overhead grounded wire is somewhat hidden in obscurity, due to the fact that the engineers of that date were not prolific in writing up their engineering feats. The earliest application of parallel grounded wires that the writer has been able to get track of was made by Mr. C. C. Chesney on the original polyphase transmission plant at Housatonic, Mass. in 1891. It seems that the next plant to use it was the Montreal Light, Heat and Power Co. transmitting power from Shambley Falls to Montreal. The overhead grounded wire gradually found its way into practise by reason of the strong endorsements of a number of engineers, notably among whom was Dr. C. P. Steinmetz. The use of overhead grounded wire was a mooted problem among engineers over a period of many years.

II—Analysis of the Uses of the Overhead Grounded Wire

The first question to settle in discussing the overhead grounded wire is its purpose. Its primary use is of course for protection against lightning and it is recognized also as a strengthening support between towers. Mr. J. Lawson has recently stated that the grounded wire on a wooden pole line is used also as a means of testing for defective insulators. The three recognized uses then are: lightning protection, mechanical support for towers and poles, and a test circuit. The use which is of interest in the following discussion is solely that as a protector against electrical and magnetic disturbances in the surrounding atmosphere.

Even as a protector against lightning the function of the grounded wires may be subdivided into at least four categories: First, the vertical grounding wire, second, a lightning rod extending above the line, third, electrostatic induction in the horizontally situated wires, and fourth, electromagnetic induction.

III—FIRST CATEGORY—PROTECTION AGAINST THE SPLITTING OF POLES BY THE VERTICAL CONDUCTOR WHICH AT ONE END IS BURIED IN THE EARTH AND RUNS THE HEIGHT OF THE POLE

This part of the grounded wire system has been used from early times in telegraph construction quite independent of the horizontal grounded wire which parallels the power wire, and is still standard practise for telephone and telegraph circuits. Every fifth wooden pole is protected this way. As such, this vertical grounding wire is a protection not against electrostatic induction or electromagnetic induction, but against the damaging effect on wooden poles of a direct bolt of lightning. This vertical grounding wire performs the same function when used in combination with the horizontal wire and at the same time it is an essential part of the horizontal wire in protecting against induction by acting as an earthing contact to the horizontal wire. How frequently along the line these vertical earthing wires should be used is a question of importance to be discussed as the subject is developed.

IV—SECOND CATEGORY—A LIGHTNING CONDUCTOR EXTENDING ABOVE THE TOP OF THE POLE OR TOWER IS DESIGNED TO ACT AS AN ELECTRODE TO THE BOLT FROM THE CLOUD

The value of this rod lies in the possibility of its greater height keeping the arc flame from being blown between the phases of the power wires, which would cause a short circuit. Used as such, it has nothing to do with the electrostatic induction and functions only in cases of direct stroke on the line. To the writer's knowledge its value has never been definitely determined by calculations, experimentation, or use. Its use has not been very great. The extremely intense electric force and potential gradient in the path of the direct stroke of lightning brings the value of the lightning rod into question. Even if the rod is high enough to keep the ionized flame away from the power wires it must yet be determined if the intensity of electric field, induced on the power wires adjacent to the lower end of this lightning rod, is not great enough to cause a side flash from the rod to the power wires, on account of the so-called isolated capacitance of the power wires. With a power wire supported on an insulator having a grounded metal pin it seems safe to hazard a guess that there will be a side flash which would either puncture the insulator or cause a flash around the skirts. The puncture distance is of the order of one inch only, and the flashover distance is of the order of one foot (30.4 cm.) Furthermore, the equivalent sphere gap of this flashover distance, due to the effect known as creepage spark over the surface of the insulator, is only of the order of a few inches at best.

When a wooden cross-arm is used and when the power wires are highly insulated by a string of many suspension disks the chances of side-flash are greatly reduced and consequently the lightning rod comes into the realm where its practicability and use are worthy of consideration and debate.

An endeavor is here made to enumerate the elemental factors involved. There are two conditions to be avoided:

First, to keep conducting arc vapors of the direct lightning stroke away from the power wires.

Second, to prevent a bolt from striking midway between poles. Cases are known where such strokes have melted the wires in two, even where the line was yet under construction and grounded at some distance from the point of the lightning stroke.

Who is to say how far down on the lightning rod the crater of the arc will extend? Taking Dr. C. P. Steinmetz' estimate of 10,000 amperes for the average current in a lightning discharge, will the crater, during its brief life, extend below the point of the rod? The heated gases will tend to rise. The heavier the wind the more rapid is the arc flame broken up and cooled. Perhaps some of the many photographs of lightning may throw some light on this problem.

The protection against direct bolts striking the wire between poles may be determined roughly by the following methods: First, for a wire supported on pin-type insulators on wooden poles, the wire may be assumed roughly to follow the arc of a circle, the center of which may be determined. It may be assumed that if the lightning strikes well into this imaginary sector the chances of its turning and reaching the pole are rather remote. Second, if a lightning rod is used or the wires are underhung by suspension insulators, the chances of a lightning stroke reaching the wire rather than the tower or lightning rod are very much lessened. Fig. 1 is drawn on the basis of making the distances from the tip of the tower and the nearest point on the wire equal. The higher the rod or tower above the line, the less the chance of a stroke reaching the line wire, other things being equal. The expression, "other things being equal" is intended to take into account the fact that a lightning discharge does not necessarily take the shortest path to the nearest object, be it earth or an adjacent cloud. The location of the electric stress depends primarily on the accidental location of condensation of moisture in the atmosphere. Otherwise, if there is no free electricity given off in the atmosphere, the discharge will take place over the shortest path between electrodes.

While this method is admittedly crude, it is the only one available to give a comparison of the immunity of different constructions. By its use some idea can be gained of the advantages of lightning rods and the underhung construction. The evident dangers from a stroke reaching the line is that of burning the wire in two and letting it fall to the ground.

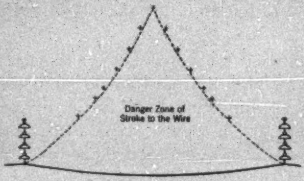


FIG. 1

If lightning gets inside the danger zone shown it is more likely to strike the wire than the tower. The curve is drawn on the basis of equal distances between the insulator and the wire. Direct strokes on the wire may fuse it in two.

With a string of six disks and the midpoint of a 500-foot span of wire 30 feet below the top of the tower the peak of the sector is 1050 feet above the midpoint of the span. With a pin-type insulator, a span of 100 feet and a sag of 2 feet, the peak of the sector is 650 feet above the midpoint of the span of wire. A 6-foot lightning rod added to the latter case lowers the peak of the sector to 160 feet and bands inward as shown in the above figure.

Should a lightning rod be sharp pointed? The early work done by Dr. Steinmetz on corona of needle points and later the work of Mr. F. W. Peek and others on corona would seem to indicate that the sharp end would have no particular value. Induced potentials of corona value often occur during storms. The formation of corona gives immediately the equivalent of a blunt end. The relief of the atmosphere by the discharge of corona is apparently too local and of such a small part of the volume of the electrostatic field of the atmosphere above the line to decrease appreciably the energy of a lightning stroke.

These questions are still in the speculative field and must be left, as refinements, to be cleared up by later work. The rest of the subject is of more importance at present and a solution is more definitely in sight.

V—GENERAL PROBLEMS OF THE PARALLEL GROUNDED WIRE

There are several factors to be taken into account in the process of determining the protective value of the grounded wire.

1. Strength of electric field in the neighborhood of the line wires.

2. The direction of the gathering charge in the cloud, that is, the path of the discharge relative to the line, parallel or perpendicular to the line before it turns vertically downward to the earth.

3. The screening effect obtained by the use of several wires, with and without grounded wires.

4. The initial momentary potential induced on a wire at the instant the cloud discharges to earth.

5. An instant after the lightning discharge has taken place, the sudden increase in capacitance between the power wire and the adjacent parallel grounded wire.

6. The effect of the number and location of parallel grounded wires.

7. The effect of electromagnetic induction between the horizontal part of the grounded wire and the parallel power wires, in which the energy of the lightning charge on the grounded wire is more or less transferred to the power wire, instead of being dissipated in the earth. High frequencies are produced in this transformation.

8. The gradual transference of the charge which travels along the power wire to the successive sections of the grounded wire and its dissipation in the earth.

VI—Getting a Reasonable Mathematical Cloud

In the mathematical analysis of the electrostatic phenomena only the simplest forms,—such as cylinders, spheres, ellipses,—lend themselves to a practicable solution. The limitless variations in the forms of storm clouds make it impossible to select a form which might be considered the average for a thundercloud. Therefore it is necessary to turn from the cloud to the local electric field near the earth which is, after all, the center of interest. At the surface of the earth all forms of clouds give one common characteristic, namely a fairly uniform, perpendicular directed electric force over a limited area. It is assumed at present that the surface of the earth is smooth. In making the mathematical analysis we are, therefore, privileged to choose any form of cloud that gives this uniformity of field near the earth. Since we are to study first the electrostatic induction on overhead wires it is natural to choose, as a matter of simplification, a cylindrical cloud parallel to the line. In the early study, lengths of wire only one centimeter long will be dealt with and therefore over many centimeters any sort of a cloud can be considered cylindrical.

In any cylindrical conductor from which a charge of electricity emanates there is a central point where all the lines of force would meet if they were extended everywhere through the surface of the cylinder. Mathematically this point is well-known as the inverse point of a circle. Electrically it is better described as the apex of charge. The apex of charge is that point which, if all the charge were concentrated there, would give the same effect as it does distributed over the surface.

It is recognized that a cloud is not a good conductor but due to its mobility to the movement of electricity by brush discharge, it is assumed that the cloud will act like a cylinder of equal dimensions. Since this does not affect the distribution of field near the surface of the earth it seems a permissible assumption to make and is a great convenience in making calculations. (Fig. 2)

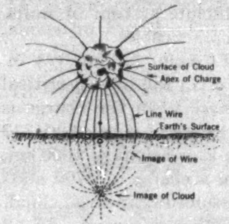


FIG. 2
Cloud of cylindrical cross-section, its electric field, its image, and a line wire in the field.

The apex of charge of the cloud will be found and calculations will be made assuming that the charge of the cloud is concentrated along this apex of charge as if it were a conducting wire parallel to the line wires.

VII—CHOICE OF THE HEIGHT OF A CLOUD

In absolute measure, the first effect of an increase in the height of a cloud would tend to decrease the electric force, and consequently electric induction, on overhead wires. An increase in the total charge on the cloud increases the quantity induced on the line wires. All we can say at present is that actual clouds will cause more or less severe induction on the overhead wires and let it rest at that. The object we have in view is to choose a height and dimensions of a cloud such as to give a uniform field in the neighborhood of the power wires. If the apex of the cloud is a few times as high as the line wires, it is found sufficient. A height of 55,000 cm. is chosen, however, for the position of the apex of the charge of the cloud. This value will be retained as a standard of reference for all future calculations.

VIII—CHOICE OF A GIVEN CHARGE ON A CLOUD FOR USE IN MAKING COMPARATIVE CALCULATIONS OF PROTECTION WHICH MAY BE EXPECED FROM PARALLEL GROUNDED WIRES—AND OTHER DATA

A reasonable cloud charge is chosen arbitrarily as one which will induce a charge on a single overhead wire of corona intensity. It is found that such a cloud charge with its apex at 55,000 cm. height can be made to give very mild intensities of charge or potential gradients in the cloud itself, and such a cloud seems satisfactory enough as a basis of comparing induced charges on line wires.

All calculations are made in the absolute system of units. Anomalously, the practical system is impracticable.

An overhead wire of a usual radius of 0.5 cm. (about 3/8 in. in diameter, approximately No. 000 B. & S.) will have a critical corona gradient of potential at its surface when the charge is about 25 statcoulombs per centimeter length of wire (0.001342 coulomb per mile.*) Placing this wire at a height of 1000 cm. above the surface of the earth calls for a charge of 5700 statcoulombs per centimeter length of the assumed cylindrical cloud, to bring the grounded wire to the condition of corona. In all future calculations this constant cloud charge will be used.

One other assumed dimension is made, namely 10,000 cm. from the apex of charge in the cloud to the lower surface of the cloud. The assumed and calculated factors are given in the following list:

Apex of charge of the cloud, 55,000 cm. (1804 ft.) above earth.

Radial distance apex to surfaces, 10,000 cm. (328 ft.)

Height of wire used as standard of comparison, 1000 cm. above the surface of the earth (33 ft.)

Quantity of electricity induced on this line wire, 25 statcoulombs per centimeter length of wire (0.001342 coulomb per mile).

Quantity of electricity in the cloud, 5700 statcoulombs per centimeter length of the cylindrical cloud (0.306 coulomb per mile).

Potential at the surface of the cloud, 26,224 statvolts (7,867,200 volts).

Potential gradient at the lower surface of the cloud, 1.254 statvolts per centimeter of vertical distance (376.2 volts per centimeter). The gradient to produce corona is nearly 100 times as great, *i. e.* 30,000 volts per centimeter. Expressed in inches and feet, the potential gradient is 956 volts per inch and 11,472 volts per ft.

The field intensity at the surface of the earth is 0.4147 dyne, and correspondingly the potential gradient is 0.4147 statvolts per centimeter. (124.4 volts per centimeter = 3800 volts per ft.)

---

*$f = \frac{2q}{r} \quad q = \frac{fr}{2} = \frac{100 \times 1/2}{2} = 25$

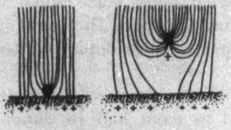
Dielectric displacement at the surface of the cloud is 0.1 statcoulomb per square centimeter of cross-section of the field.

Dielectric displacement at the surface of the earth directly under the cloud is 0.033 statcoulomb per square centimeter of earth surface.

NOTE: The undisturbed field intensity, potential gradient, and dielectric displacement at a height above the surface of the earth corresponding to line wire heights are sensibly the same as the values given above for the surface of the earth. Therefore, over the range of height corresponding to the usual height of a line wire the potential may be obtained, theroetically, by calculating the product of the height and potential gradient (V = centimeter height × 0.4147). The general relations are shown in Fig. 2. The calculations are made by equations (**1**) and (**2**) in the mathematical section.

IX—THE INDUCED CHARGE ON A SINGLE WIRE AT VARIOUS HEIGHTS FROM THE EARTH

The value of induced charge, initally at zero potential, is the second step in the determination of the voltage on the line which will suddenly appear when the cloud discharges to earth and sets free the bound charge on the line. We have just noted in the previous paragraph that the inducing potential is proportional to the height above the earth. The induced quantity at increasing heights does not, however, follow in direct proportion due to the change in capacitance of the wire. Above a height of 1000 cm. (33 ft.) the increase in the quantity of electricity induced is almost a linear relation to the height of the line. This law holds up to and somewhat beyond 4000 cm. At less heights than 100 cm. the charge falls off more rapidly on a slightly curved line. The actual values are given in Table I, 3d column. These quantities are obtained by a solution of equation.



FIGS. 3 and 4

Illustration of the cross-section of the electric field in the neighborhood of a wire, Fig. 3 on the ground and Fig. 4 in the air. The latter gathers in the field from each side nearly in proportion to its height.

$$V_1 = 0 = \left(4.6 \log_{10} \frac{m_{11}}{r_1}\right) q_1 - \left(4.6 \log_{10} \frac{m_{c1}}{r_{c1}}\right) q_c$$

Whence—

$$q_1 = \left(\log_{10} \frac{m_{c1}}{r_{c1}} \frac{r_1}{m_{11}}\right) q_c$$

At 1000 cm. high, we have assumed a charge of 25 statcoulombs per centimeter length of the wire. At 2000 cm. high the induction would be 46.4 statcoulombs per centimeter length of wire, using the same inducing charge in the storm cloud. At 4000 cm. high, the wire would have induced on it 85.7 statcoulombs per centimeter length of it. Fourteen different heights are given in Table I, which also gives the quantity on the wire as a fraction of the total charge in the cloud. For example, at 1000 cm., the charge on the wire is 0.00439 part of the charge in the cloud.

There is given also in the table the total width of electric field that is gathered in by the wire. For example, the wire at 1000 cm. (33 ft.) gathers in the field from each side for a distance of 379 cm. (12.4 ft.), making a total width of 758 cm. (24.9 ft.). This electric field would normally go straight to the earth but due to the presence of the grounded wire is drawn toward the wire and a large part of it passes through the horizontal plane of the wire and is looped back up as is shown in Fig. 4.

At a height of 2000 cm. (65.6 ft.) the overhead grounded wire draws a field in from each side from a distance of 704 cm. (23.1 ft.).

A more satisfactory analysis of what takes place when a grounded wire is raised to different heights above the earth is shown in the two sketches, Figs. 3 and 4, which depict values taken from the table.

If a bare wire is lying on the ground (Fig. 3), it will take an electric charge which is proportional to about half its superficial area. The earth itself has a charge of 0.033 statcoulomb per square centimeter due to the charge of the cloud. Therefore, the charge on the wire lying on the ground will be of this order. When the wire is raised off the surface of the earth, as is shown in Fig. 4, a few of the lines near the wire which before found an easier path to the earth, now find a shorter path by bending around to the wire. The lines of force just beyond this width find a more desirable path to the ground than to the wire but due to the removal of part of the electric field directly underneath the wire these lines are bent under the wire in their path to earth.

The width of field drawn into the wire is obtained by dividing the charge emanating from the wire by the number of statcoulombs of displacement per square centimeter, due to the cloud.

Table I gives the heights of wire, fraction of the cloud charge which ends on the wire, quantity statcoulombs per centimeter length of wire, percentage of same referred to a wire at 1000 cm. height, the width of the field drawn into the wire at the height given, atmospheric quantity is 0.033 statcoulombs per centimeter and the potential gradient is 0.4147 statvolt per centimeter.

TABLE I.

Height of wire dia. 1 cm.	Part of cloud charge on wire	Statcoulombs quantity per cm. length of wire	Per cent of quantity at height of wire of 1000 cm.	Width of field picked up by wire, cm.	Atmospheric potential at height given	
					Statvolts	Kilovolts
100 cm.	0.000633	3.610	14.4	119.5	41.47	12.44
200 cm.	0.001085	6.180	24.7	187.5	82.94	24.882
400 cm.	0.00196	11.164	44.6	338.8	165.88	49.764
800 cm.	0.00360	20.535	82.1	623.0	331.76	99.528
1000 cm.	0.00438	25.000	100.	758	414.7	124.4
1100 cm.	0.00476	27.170	108.7	824	456.17	136.85
1200 cm.	0.00514	29.277	117.1	888.	497.64	149.29
1600 cm.	0.00663	37.821	151.3	1148	663.52	199.056
2000 cm.	0.00815	46.422	185.7	1410	829.4	248.82
2400 cm.	0.00950	54.169	216.7	1642	995.28	298.58
2800 cm.	0.01090	62.200	248.8	1887	1161.16	348.348
3200 cm.	0.01235	70.516	282.1	2140	1327.04	398.112
3600 cm.	0.01370	78.092	312.4	2370	1492.92	447.876
4000 cm.	0.01502	85.668	342.7	2600	1658.8	497.64

X—THE INDUCED CHARGE ON A SINGLE OVERHEAD WIRE AS AFFECTED BY ITS SIZE

As a convenient size for reference a diameter of one cm. for the overhead wire has been chosen and on this is induced 25 statcoulombs per centimeter length of wire (0.001342 coulomb per mile).

The first step will be to reduce the size of wire. As a rough approximation, take one strand of a seven-stranded cable and let us assume an equivalent diameter of one-third which is a radius of 1/6 cm. This wire will have induced on it by the storm cloud 22.1 statcoulombs which is 88 per cent of the quantity induced on the wire of one cm. diameter. The reduction then in the weight of the wire approximately to 1/7 has reduced the quantity of electricity drawn in by the overhead grounded wire by only 12 per cent. This is a good illustration of the slight effect that the size of the overhead wire has in gathering in the electric field. The same statement is true for sizes of wire larger than the one of diameter of one cm. If the weight of the wire is increased four times, that is to say, with an increase in the diameter from one cm. to two cm. the quantity of electricity terminating on the wire increases only 10 per cent. If the weight of the wire is increased sixteen times, which corresponds to an increase in the diameter from one cm. to 4 cm., the quantity of electricity terminating on this wire from the same storm cloud will be only 20 per cent greater if the weight of the wire is increased 64 times, which corresponds to an increase in the diameter from one cm. to eight cm., the quantity of electricity terminating on this wire will be only 33.6 per cent greater.

We may conclude from these data that calculations of electrostatic induction made for a wire of 0.5 cm. radius will give approximations for all other wires of usual practise.

INDUCING A CHARGE ON AN OVERHEAD WIRE WHICH IS NOT GROUNDED

From experiences in the laboratory in electrostatic induction such as the electrophorus, where it is necessary to ground the metal plate while it is near the charged wax plate in order to get it to take a charge, it is sometimes erroneously assumed that it is necessary to have an overhead wire grounded somewhere in order likewise to get it to take a charge from cloud induction. Contrary to this assumption, it may be stated that, in general, a system with a non-grounded neutral and absolutely no leakage over the insulators charges up with about the same quantity under the storm cloud as a system with a grounded neutral. The exceptional case is the short length of circuit.

Laboratory experience may give inadequate conceptions of the conditions outdoors and the local characteristic of a cloud lightning. It is not a question of how many square miles the storm cloud covers but only what extent of electrostatic field between cloud and earth is relieved by the lightning stroke. We are accustomed to seeing the visible part of the streak a mile or so long only. If the streak in the cloud is parallel to the transmission line, relief over a corresponding length is given to the charge induced on the line wires. But the transmission wires extend miles beyond this influence and it is the capacitance of wire to ground in the extended lengths not directly under the influence of the storm cloud which allows a non-grounded wire to take an induced charge.

Fig. 5 shows a short length of wire not extending beyond the field of the cloud. The wire takes the potential of the air at the same height. The corresponding d-c. stress is thrown on the insulation of the apparatus until the lightning stroke takes place. After the lightning stroke there is no charge on the line, and the potential of the line wire returns to normal without the presence of the usual traveling waves. For the traveling wave there has been substituted a d-c. stress over a period of time depending on the rapidity of formation of the storm cloud. Leakage over the insulators will enter, of course, to give the line more or less of a charge. There will be a momentary oscillation between line and apparatus.

Now turning to the more usual condition of a non-grounded circuit, Fig. 6 shows how the cloud induces a charge under it without leakage to ground. The large part of the line not under the cloud acts as a condenser of large capacitance which absorbs the relatively small quantity induced by the cloud without causing much rise in line potential. $[V = Q \div C]$ The relations between the induced quantity and potential on the line wire are somewhat unusual. When the quantity is zero the induced potential (by the assumed cloud) is 414.7 statvolts. On the other hand, when the potential is zero, that is to say, the wire is grounded, the quantity is 25 statcoulombs. The intermediate conditions are shown by the straight line in Fig. 7.

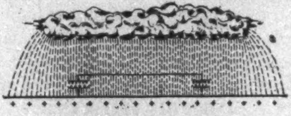


FIG. 5

Illustration of a short line under a long cloud. This line can become charged by leakage to ground only.

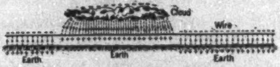


FIG. 6

Illustration of a long line under a short cloud. This line can become charged without any leakage of current to ground, that is to say, without any grounding.

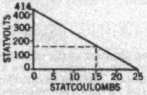


FIG. 7

The relations between induced quantity and potential on a non-grounded line wire. [000 B. & S. wire, 1000 cm. (33 ft.) high and a field of 0.414 statvolt per cm. (potential gradient.)]

$$V + 16.6q = 414.7$$

For different relative lengths of line under and not under the cloud the following conditions hold: If there is one mile under the cloud and nine miles of line not under, the potential of the wire will be 41.47 statvolts, $[1 \div (9 + 1)]414.7$. The quantity will then be $0.9 \times 25 = 22.5$ statcoulombs.

If, again, the relative lengths are two miles and 98 miles, the induced potential will be 2 per cent of $414.7 = 8.3$ statvolts and the induced quantity will be 98 per cent of $25 = 24.5$ statcoulombs.

Now, when the cloud discharge takes place there are two traveling waves, namely, the wave due to the concentrated charge under the cloud, and the wave due to the distributed charge throughout the rest of line and coils of the apparatus. These waves move in opposite directions and, since they are of opposite signs of electricity, as the concentrated wave passes through the distributed wave it will lose its potential in proportion to the cancellation of quantity.

It should be noted that the distributed charge has a quantity located down in the coils of generators and transformers depending on the local capacitance of the coils to the earth. After the cloud discharge, this lightning is inside the apparatus and must get out. In so doing it must bump into the inductance of each adjacent coil and be reflected more or less. Incidentally, this is a source of high-frequency oscillations. An attempt is made to represent these conditions in Fig. 8.

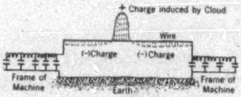


FIG. 8

The shaded parts on the overhead line shows the location of the two separated charges. The coils and condensers at the end of the line represent the conditions in a generator or transformer. Each coil is charged as a condenser by the lightning cloud.

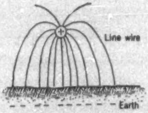


FIG. 9

The field of the induced charge on a line wire at the instant after the storm cloud discharges to earth.

FUNDAMENTAL LAW OF INSTANTANEOUS POTENTIAL AND QUANTITY IN CASES OF INDUCTION

It is purposed to show the simple method of obtaining the potential after the lightning discharge has turned free the previously bound charge on the line. To do this the movement of electricity in the cloud at the beginning and during the discharge of the lightning will not be considered now, but will be the subject of a later paragraph. As a further simplification the wire will be assumed grounded through either a resistance or inductance, so that its potential may be considered zero during the period of electrostatic induction.

At 1000 cm. up from the surface of the earth, the chosen cloud produces 414.7 statvolts (124,410 volts). A grounded No. 000 wire (one cm. diameter) at this height will take a charge of 25 statcoulombs by electrostatic induction. When the cloud discharges, the field which extends between wire and cloud will suddenly flop over (with more or less oscillation according to the nature of the lightning bolt) and appear as a field between wire and ground. The bound charge has been shown already in Fig. 4. The freed charge is shown in Fig. 9.

The potential will be given by the equation $V = Q \div C$ where Q is the quantity per unit length and C is the corresponding capacitance between wire and ground per unit length.

The object of this paragraph is to point out that to obtain the final potential rise of the wire it is unnecessary to calculate either the induced quantity or the capacitance of the wire. The potential of the wire immediately after the cloud discharge is the same as existed at this height with no wire present, namely 414.7 statvolts (124,410 volts).

This is a fundamental law and applies equally well to any number of overhead wires. It will be shown later that the addition of every wire on a pole reduces the quantity of electricity induced on each wire but it does not reduce the instantaneous potential of the freed charge. If a second wire is placed at a height of 1100 cm. (100 cm. above the first wire) the instantaneous potential after the lightning discharge is found by multiplying the undisturbed potential gradient in the atmosphere by the height of the wire; thus, 1100 cm. × 0.4146 statvolts per centimeter gives 456 statvolts (136,800 volts). The first wire again assumes a potential of 414.7 statvolts.

SCREENING OF ENERGY INDUCED BY THE USE OF SEVERAL PARALLEL WIRES ON THE SAME POLE

It has just been stated in a fundamental law that the presence of several wires does not decrease the instantaneous potential at cloud discharge although there is a decrease in quantity per wire due to the presence of several wires. (Nothing is being said at present of grounded wires.) The several wires produce a screening of quantity without a useful effect on the resultant instantaneously induced potential. There is, however, a useful screening effect of energy in the surge.

For example, with one wire alone the induced quantity is 25 statcoulombs per centimeter length of wire. The instantaneous potential of the electric wave is 414.7 statvolts and the instantaneous electrostatic energy is 5180 statjoules or ergs per centimeter. Placing a second wire of the same diameter and at the same height but spaced 100 centimeters reduces the quantity on the first wire from 25 statcoulombs to 18.36 statcoulombs per centimeter. The energy is thereby reduced to a corresponding amount (73.4 per cent), that is, to 3805 statjoules per centimeter. There is less energy in the wave on each wire to be dissipated. However, the total quantity is increased from 25 to 36.72 statcoulombs per centimeter and the total energy from 5180 to 7610 statjoules. The quantity and energy are equally divided between the two parallel wires because they are the same size and at the same height.

① one wire (overhead). Electric field constant.
q-25 statcoulombs on a No. 000 wire
① ②
q-18.36 18.36 Quantity total-36.7
③ ① ②
q-15.70 13.65 15.70 Total-45, Average-15
⑤ ③ ① ② ④
q-13.4 10.6 9.94 10.6 13.4 Total-57.94, Av.-11.59
⑦ ⑤ ③ ① ② ④ ⑥
q-12.42 9.44 8.21 8.09 8.21 9.44 12.42
Total-68.23, – Av.- 9.75

FIG. 10

Induced charges on line wires by a constant electric field. Wires are No. 000 and spaced 100 cm. (39.4 in.) horizontally. Five groups separately, each group 1000 cm. (33 ft.) above the surface of the earth. Groups; 1 wire, 2 wires, 3 wires, 5 wires, and 7 wires. All quantities are given in statcoulombs per cm. length of wire.

In conclusion: Increasing the number of parallel wires decreases the energy in the surge per wire without decreasing the initial instantaneous potential. The closer the wires to each other, the greater the reduction in energy. As a limit, the reduction in energy, even if the wires are so close as to touch is a little less than inversely proportional to the number of wires. For example, two wires cannot reduce the energy to quite half of what would be induced on one. At the other extreme, when parallel wires are far enough apart to be outside each others fields they exert no screening effect on each other.

The numerical values above (Fig. 10) are calculated by equations (**5**), (**6**), (**7**), (**8**), and (**9**) (mathematical section). The general equations are given in equations (**12**) and (**13**).

For No. 000 wires in a vertical plane, 100 cm. spacing, the quantities induced are given in the following list. The central wire is always numbered 1, and the even numbers are assigned to the right and symmetrically placed wires to the left are assigned the next odd number, thus, (3) (1) (2)...

Wire one only $q_1 = 25$ statcoulombs per centimeter length of wire. Two wires $q_1 = q_2 = 18.36$.

The last diagram with four wires grouped around one wire shows an average reduction in quantity from 25 to 10.8 statcoulombs per centimeter which gives a reduction in surge energy to 43 per cent average per wire, other lightning conditions being equal. The equations for this group are (**14**), (**15**), (**16**) and (**17**) in the mathematical section.

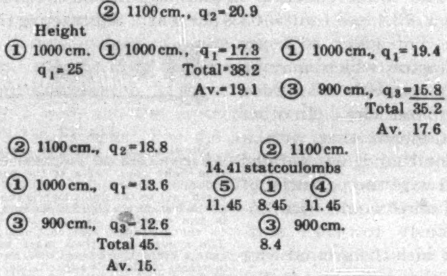

② 1100 cm., q_2=20.9
Height
① 1000 cm.
q_1=25
① 1000 cm., q_1=17.3
Total=38.2
Av.=19.1
① 1000 cm., q_1=19.4
③ 900 cm., q_3=15.8
Total 35.2
Av. 17.6
② 1100 cm., q_2=18.8
① 1000 cm., q_1=13.6
③ 900 cm., q_3=12.6
Total 45.
Av. 15.
② 1100 cm.
14.41 statcoulombs
⑤ ① ④
11.45 8.45 11.45
③ 900 cm.
8.4

FIG. 11

Induced charges on line wires by a constant electric field. The five groups are to be considered separately. Size of wire No. 000, spacing 100 cm. Quantities induced at the given heights as given above. All quantities are given in statcoulombs per cm. length of wire.

USE OF A PARALLEL GROUNDED WIRE. SCREENING AND INCREASE OF CAPACITANCE OF LINE WIRES

The grounded wire produces no more screening effect than a power wire in its place. Also it may not, at the first instant of cloud discharge, reduce the potential induced on a power wire, except at the pole where the vertical riser from ground is connected to the parallel ground wire. If the lightning stroke were absolutely instantaneous, or if the distance from the induced charge to the grounding pole were great the parallel grounded wire would rise to the potential it would have if it were not grounded. Since the lightning bolt requires time to form, some of the quantity set free on the parallel grounded wire will have time to pass down the vertical connection to ground and immediately becomes the seat of a charge induced by the charge on an adjacent parallel power wire.

The three stages are shown in Fig. 12.

The grounded wire increases the capacitance of the power wire and thereby reduces its potential without in any way reducing its charge. The capacitance to earth of the one wire alone at 1000 cm. height is 0.0603 statfarad per centimeter (10.78 millimicrofarads per mile). The capacitance of the same wire to the combined surface of the earth and the parallel grounded wire, 100 cm. separation, is 0.0693 statfarad per centimeter. Therefore, the reduction in potential due to increase of capacitance alone should be to 87 per cent. The quantity, by screening, was reduced from 25 to 18.3 statcoulombs (73.4 per cent). The total reduction in potential will be the product 87 per cent × 73.4 per cent = 63.8 per cent. Subtracting this from 100 per cent gives 36.2 per cent, a factor which may be called the protection afforded by the ground wire. In other words, it means that with a given cloud and no parallel grounded wire the potential of a power wire would rise instantaneously to 414.7 statvolts but with the ground wire in place the same cloud discharge will cause a rise of only 264.7 statvolts. This is a voltage ratio of 63.8 per cent, or a protection of 36.2 per cent of the potential which would have existed without the guard wire.

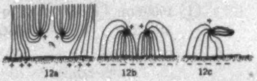


FIG. 12

Showing three stages of charge on one power wire and one parallel grounded wire (the right one). 12-a is the condition of induction before the cloud discharges to earth (not to the line). 12-b is the condition at the instant the cloud is discharged. 12-c. is the condition as soon as the charge on the grounded wire can pass to earth. The ground wire then takes an induced charge from the power wire and thereby increases the latter's capacitance.

PROTECTION AFFORDED BY ONE PARALLEL GROUNDED WIRE

In the previous work two steps were taken in the calculations simply to show the two theoretical factors involved, namely screening and increased capacitance. By treating the equations symbolically most of the factors cancel out in the two steps, leaving a very simple formula which gives the protection in one calculation.

Taking first the case of two wires in a horizontal plane, one a grounded wire, the

$$\frac{\text{Potential protected}}{\text{Potential unprotected}} = \frac{a - b}{a}$$

$$\text{where } a = 4.6 \log_{10} \left(\frac{2 \times \text{height of gr. wire}}{\text{radius of grounded wire}} \right)$$

$$b = 4.6 \log_{10} \left(\frac{\sqrt{(2\ \text{height})^2 + (\text{spacing})^2}}{\text{spacing}} \right)$$

$$\text{and the protection} = \frac{b}{a}$$

The symbolic solution is shown in equations (**18**) to (**27**) inclusive.

The equation shows that the protection decreases as the distance between the wires in the horizontal plane increases in accordance with the logarithm of a ratio. For a No. 000 wire one cm. in diameter and 1000 cm. (33 ft.) high, the factor a = 16.6. Various values of b are given as follows: For 50 cm. (19.7 in.) spacing from the grounded wire the factor b = 7.38 and the protection is 44.5 per cent. For 100 cm. (39.4 in.) spacing, b = 6, and the protection is 36.3 per cent. For 200 cm. (78.7 in.) spacing, b = 4.6 and the protection has fallen to 27.7 per cent. At 500 cm. (197 in.) spacing, half the height, b = 2.83 and the protection is 17 per cent. Lastly at a spacing equal to the height, viz. 1000 cm. (33 ft.), b = 1.61 and the protection is 9.7 per cent.

The protection is entirely independent of the size of the power wire. This is due to the fact that as the power wire is increased in size it has induced on it a greater quantity, but this is compensated by an equally greater capacitance to the earth and grounded wire. This is proven mathematically in the symbolical equations (**18**) to (**28**).

There is another simple relation. So long as there is but one grounded wire, the equation just given applies individually to any number of wires in a horizontal plane. Each calculation is made quite independently. The equation does not apply for two or more parallel grounded wires.

PROTECTION OF WIRES STRUNG IN A VERTICAL PLANE

The ratio of potentials (protected to unprotected) depends on the relative height of the grounded wire and power wire. For example, if the power wire (No. 2) is hung 100 cm. (39.4 in.) under the grounded wire, then due to the height alone the ratio of potentials will be decreased by the ratio of heights, 900 cm. ÷ 1000 cm. = 0.9. The factor previously designated by the symbol b will also change somewhat. Thus,

$$b' = 4.6 \log_{10} \left(\frac{(2 \times \text{height of grounded wire}) - \text{spacing}}{\text{spacing}} \right)$$

This equation for b' applies when the grounded wire is above the power wire. If the contrary condition is true, then the "spacing" given in the numerator is to be added instead of subtracted. The potential ratio for vertically situated wires is:

$$\text{Ratio} = \frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{a - b'}{a} \, \frac{h_2}{h_1} \qquad \textbf{(28a)}$$

Where h_1 is the height of the grounded wire and h_2 the height of any power wire strung in the vertical plane beneath.

Examples: Parallel grounded wire No. 000 (1 cm. diameter) at a height of 1000 cm. (33 ft.). Power wire, of any diameter, at 900 cm. directly underneath,

$b' = 5.89$ and the ratio

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{16.6 - 5.89}{16.6} \, \frac{900}{1000} = 58\%$$

With the power wire 100 cm. above the grounded wire,
$b' = 6.085$ and the ratio

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{16.6 - 6.085}{16.6} \, \frac{1100}{1000} = 69.7\%$$

Exchanging positions of the power wire and grounded wire $a = 16.78$, $b' = 6.085$, and the ratio

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{16.78 - 6.085}{16.78} \, \frac{1000}{1100} = 57.9\%$$

Now keeping the grounded wire above, raise the power wire to double the height, viz. 2000 cm. (66 ft.) and double the spacing to 200 cm. (78.7 in.), the factor a = 18, $b' = 6.085$ again, and the

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{18 - 6.085}{18} \, \frac{2000}{2200} = 60.2\%$$

For a second power wire hung 200 cm. (78.7 in.) under the first power wire, $b' = 4.6$, and the ratio

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{18 - 4.6}{18}\,\frac{1800}{2200} = 60.9\%$$

For the third phase wire hung 200 cm. (78.7 in.) below the second wire, $b' = 3.69$ and the ratio

$$\frac{\text{Pot. protected}}{\text{Pot. unprotected}} = \frac{18 - 3.69}{18}\,\frac{1600}{2200} = 57.8\%$$

Subtracting each of the above ratios from 100% gives the degree of protection.

Attention is drawn to the greater protection given to the lower wire as compared to the one just above it. There are two factors involved which are antagonistic. First, the protection decreases as the distance from the grounded wire to the power wire beneath is increased. Second, the protection is increased as the power wire is lower, due to the ratio of the heights.

The foregoing figures are approximately the same as obtained in the usual practise. A grounded wire $\frac{3}{8}$ in. in diameter is not much less than one cm. Towers are about 60 ft. high and spacings about six ft. Only one parallel grounded wire is usual even with two power circuits. The number of power wires has no effect on the protection against potential but, as shown previously, decreases the energy in the surge on each wire.

The single grounded wire is not usually directly over the three-phase circuit but this makes relatively little difference in the results. To give the factor b for wires in a horizontal plane and b' for wires in a vertical plane a general value, needs only the use of the well-known equation for the coefficient of quantity, thus

$$b_1 = 4.6 \log_{10} \frac{m_{21}}{r_{21}}$$

where m_{21} is the distance of the image of the power wire to the grounded wire and r_{21} is the spacing between the wires.

The laws for obtaining the best protection possible with a single grounded wire expressed in a practical form are: (1) string the power wires as near the earth as practicable; (2) string the grounded wire above but as near to the upper power wire as safe mechanical spacing permits.

PROTECTION AFFORDED BY TWO PARALLEL GROUNDED WIRES

It may be said immediately, without mathematical analysis, that the degree of protection afforded by two grounded wires depends on where the two wires are placed relative to each other. If they should, in the one extreme, be placed side by side, the added protection by the second wire would be very slight. If, on the other hand, they are placed on the opposite sides of a power wire their protection together is nearly as great as the values calculated separately and then combined.

The protection given by two grounded wires with one power wire anywhere between them, and all wires situated in the same horizontal plane is

$$\text{protection} = \frac{b + f}{c + d}$$

where the coefficients b, f, c and d are given by equations (**38**), (**39**), (**40**), and (**41**) respectively. (Mathematical section).

For example, wires No. 000, one cm. diameter, height = 1000 cm. (33 ft.) and spacing 100 cm. The central wire No. 1 is the power wire. Its coefficient a is not involved because the protection is independent of the size of the power wire. Coefficient $b = f = 6$, $c = 16.6$, and $d = 4.6$

$$\text{Protection} = \frac{6 + 6}{16.6 + 4.6} = \frac{12}{21.2} = 56.8 \text{ per cent.}$$

The potential ratio = 1 − 56.8 per cent = 43.2 per cent.

The potential ratio of one grounded wire and one power wire, previously calculated, was 63.7 per cent. Assuming, somewhat erroneously, that the real value combined is the product of the separate values, gives 63.7 × 63.7 = 40.6 per cent. This is 2.6 per cent too small but roughly approximate.

If the two grounded wires are not on opposite sides of the power wire the error of such an assumption will be materially greater.

Before pursuing further the value of the use of several parallel grounded wires it is desirable first to consider other fundamental relations in connection with electromagnetic induction which must be taken into account in deciding on the location of multiple grounded wires.

THE REACTION FROM THE LOOP OF THE GROUNDED WIRE BOTH ELECTROSTATIC AND ELECTROMAGNETIC

So far it has been assumed that the charge on the overhead wire at the instant of release by the cloud discharging to earth, passes harmlessly to earth without attending phenomena of interest. This is true, it would seem, only under exceptional conditions. This freed electric charge represents a definite energy. This energy must be either dissipated or transferred to some other circuit, since there is no way of preserving it intact in the grounded wire loop either as electrostatic or electromagnetic energy.

Each loop forms a distributed capacitance and double return circuit, Fig. 13, and shown in equivalent circuit in Fig. 14. Unless the ohmic resistance in the loop is equal to or greater than the critical damping resistance an oscillation will follow the initial discharge to earth of the freed charge. As a matter of fact, the resistance, especially of metal towers, is but of small fraction of the critical damping value. Many oscillations will therefore take place.

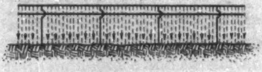


FIG. 13

Distributed charge and loop circuit to ground of a grounded wire at the instant its induced charge is freed.

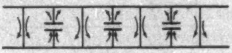


FIG. 14

The equivalent circuit and the discharge of a grounded loop.

So much for the charge induced by the cloud. The same statements apply to the charge induced on the parallel grounded wire by the charge on the power wire as shown in Fig. 12. c.

The value of this induced charge, already calculated for a steady condition, will overshoot Fig. 15. Momentarily it is possible to get nearly double the steady value.

For the present, the assumption is made that the length of line wire is no greater than the length of the inducing cloud. This is done for the sake of simplicity. It avoids the consideration of the traveling wave. On this assumption the charge which is freed on the power wire remains stationary except for local disturbances which come from the discharge of the grounded wire to earth.

Due to the electrostatic effect alone, the surge potential on the power wire drops from its initial value and oscillates across its final value. For example, for the two wires at 100 cm. separation both in the same horizontal plane and one grounded, the potential drops on the power wire from + 414.7 statvolts to + 195 statvolts and only after several oscillations does it reach its final stationary value of +264 statvolts. This oscillation takes place while the oscillation in Fig. 15 is active.

The electromagnetic effects must also be considered. The surges in the grounded wire are free to move with a velocity nearly equal to that of light. A considerable value of current will be reached. Rings of magnetism emanating from the grounded wire cut the parallel power wire and induce therein electromotive forces which are proportional to the mutual inductance between the power wire and grounded wire, and to the rate of change of current, $e = M\frac{di}{dt}$.

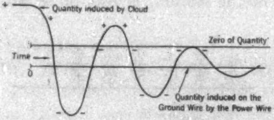


Fig. 15

The oscillation of the quantity on the grounded wire from the steady positive value at the instant it was released by the cloud discharge to the later negative value induced by the adjacent positively charged power wire.

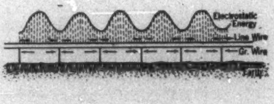


Fig. 16

The grounded wire loop is shown below the power wire. Currents are represented by arrows. The resulting humps in the electrostatic energy are depicted above the power wire.

The surge current in the parallel grounded wire will rise to its greatest value at the pole or tower where it is connected to ground by the vertical riser. The current will be zero at the center of the span. (Reason from conditions of Fig. 4).

The effect of the first half-cycle of surge current is to produce a hump of electrostatic energy midway between towers in the power wire. An attempt to depict this condition is shown in Fig. 16. As a result the main wave, only a part of which is shown in Fig. 16, will be broken up in crests, superposed on the energy induced by the direct action of the storm cloud. These crests are in fact a superposed higher frequency on a single impulse. The frequency is immediately obtainable from the distance between grounding points of the grounded wire. This distance is a wave length, as shown in Fig. 15. If there are ten towers to the mile and the velocity of the traveling wave is 183,000 miles per second the frequency will be 10 × 183,000 =

1,830,000 cycles per second. With 50 grounding points per mile the frequency is 9 million cycles per second. We have all been puzzled at times to account for the high-frequency effects of lightning in transmission circuits. Small inductances give remarkable choking effects at times. The foregoing theory has not yet had the test given by experimental evidence but it would seem to be one of the several possible causes of high frequency induced in a transmission line.

XIV—Self-Inductance, Natural Frequency, Maximum Current, Critical Resistance of the Grounded Wire and the Mutual Inductance with the Power Wire

On the assumption that the current in the part of the circuit which closes through the earth can be treated as an imaginary wire, an image at a depth under the surface of the earth equal to the height of the actual grounded wire above the surface of the earth, the self-inductance is 428 micro-henries for a length of overhead wire of 500 ft. (11,720 cm.) The capacitance of the grounded wire has already been found and from the combination of its inductance and capacitance its natural frequency is 640,000 cycles per second.

The maximum current of discharge is 569 amperes. The critical resistance which would just damp out oscillations is 370 ohms.

The mutual inductance between the grounded wire and the power wire is 179.8 micro-henries.

In these data it should be again noted that the distance between the earthing points of the grounded wire is 1000 ft. (23440 cm.) and is somewhat greater than is usual in practise. The effect of lesser distance between grounded points will be considered later.

These data show that with the usual resistance to ground at a tower of the order of 5 to 20 ohms, a great many oscillations will take place in this circuit before the energy will be absorbed in the resistance, since the critical damping resistance is 370 ohms. Since the mutual inductance is 42. 4 per cent of the self-inductance, a considerable percentage of this oscillation will be transferred to the power wire.

XV—Data on the Transfer of the Oscillating Surge on the Grounded Wire to the Power Wire

It is assumed now that the transmission wires are many times longer than the induced charge on the wires. Traveling waves will therefore follow the release of the induced charge. The primary of the circuit (the grounded wire loop) contains inductance, capacitance, and resistance. The secondary, which is the power wire, contains inductance and capacitance. From this standpoint we should use the corresponding mathematical equation but it should be noted that the capacitance of the power wire is a distributed capacitance and that as soon as a part of the charge is transferred to the power wire it does not oscillate in conjunction with the grounded loop, but the induced charge is transmitted along the power wire as a traveling wave. Since this energy is lost, in the mutual operation of the primary and secondary, the problem is similar to a secondary circuit containing a considerable resistance which absorbs energy. If these two problems give different results, it will be necessary subsequently to choose the one which more nearly fits the actual conditions.

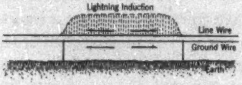


FIG. 17

Conditions of induced charges on the power wire and grounded wire at the instant of cloud discharge. Also the resulting currents.

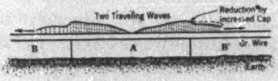


FIG. 18

The same charge as shown in Fig. 17 after it has turned into two oppositely directed traveling waves. Note the decrease in potential as each arrives at the adjacent ground loops *B* and *B'*.

Solving this problem as though the two circuits both contained concentrated inductance and capacitance without resistance, it is found that the voltage induced in the secondary is 51.6 per cent of the voltage in the primary. The initial voltage in the grounded wire, acting as primary, is 105,000 volts. Therefore there would be transferred to the line on this basis a surge which has an initial voltage of 54,000 volts and a frequency somewhat over 600,000 cycles per second. The transference of energy from the local grounded wire circuit to the power wire would very quickly exhaust the supply contained in the original surge. In round numbers the wave train would run 54 kv. first peak, 27 kv. second peak, 18 kv. third peak, 9 kv. fourth peak, 4 kv. fifth peak, etc.

On the basis of using a formula for a concentrated resistance in the secondary of these coupled circuits the results will be as follows:

To get a conception of the relations of the local oscillation in the loop of the grounded wire and the main traveling wave in a power wire, let us assume that the grounded wire is earthed only at the limits of the clouds influence.

At the instant of release, when the cloud discharges to earth, the charges on both wires start to spread simultaneously and similarly in both directions, Fig. 17. At the midway point both wires reach zero potential at approximately the same instant Fig. 18. The traveling wave on the power wire has now split into two parts and is gradually passing beyond the locality of the charged loop of the grounded wire. The grounded wire *A* has produced no decrease in potential of the power wire. When the surges on the power wire reach the adjacent grounded loops, *B* and B^1, they have their potential decreased by the added capacitance of these uncharged grounded wires.

The surge in the grounded loop continues to oscillate locally and by mutual induction, transfers a fraction of its energy to the power wire. This transferred energy cannot add directly to the main traveling wave on the power wire because the main wave has passed beyond the influence of the grounded loop, *A*. The grounded loop *A* can do nothing more than put an attenuating tail on the main wave and make of it thereby a wave train (assuming for the present purpose that the cloud discharge has caused a simple impulse). This wave train is shown in Fig. 19.

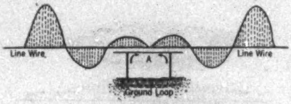


FIG. 19

Showing the tail put on to the main lightning surge by the transfer of surge energy from the grounded loop to the power wire by electromagnetic induction. The resistance of the grounded loop is less than the critical value.

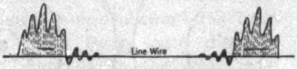


FIG. 20

Superposed higher oscillation on a traveling wave produced by the oscillations in a grounded loop. This effect occurs when the initially induced charge covers several grounding points.

If the induced charge of the cloud covers several grounded loops the two traveling waves should be a combination of Figs. 16 and 19, as represented in Fig. 20.

From these results we see another defect of the overhead grounded wire, namely that after it absorbs its part of the surge energy from the cloud it returns this energy to the power wire in the form of a wave train. According to the local conditions this wave train may be either superposed on the charge induced directly by the cloud on the power wire or it may follow immediately on the heels of this traveling wave, or both simultaneously. Although the voltages of this wave train are condiserably attenuated, the wave train may do harm to insulation. Should the coils of apparatus in any part have a natural frequency corresponding to that of the wave trains, the energy of this entire wave train may be concentrated again in this local resonant point, and consequently the potential may rise to extremely high values. This resonant condition would not occur, however, if the grounded wire had not produced the wave train.

From this standpoint, therefore, it is desirable to have a resistance in the earth connections of the grounded wire which approaches the critical damping resistance. Since there are two earth connections in this circuit this resistance should be approximately 185 ohms each.

The objection to the higher resistance in the earth connection may be found when analysis is made of the conditions of potential during a direct stroke. If, however, it is conceded that a direct stroke will invariably cause side flashes to the power wires in spite of the value of the earth resistance, this objection to the higher resistance of the grounded wire will not be valid.

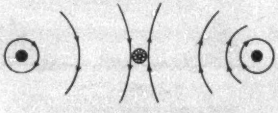


FIG. 21

A grounded wire placed on each side of a power wire so as to reduce the mutual inductance to zero.

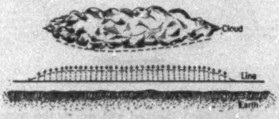


FIG. 22

Stationary induced charge on the line before the cloud discharges.

In placing a parallel grounded wire, the object should be to increase the electrostatic protection and decrease the electromagnetic induction of the ground wire surge which is transferred back to the power wires. Raising the grounded wire high above the power wires decreases the electromagnetic induction but unfortunately decreases also the electrostatic protection.

A better method of reducing the electromagnetic induction is to employ two grounded wires and place them symmetrically on each side of a power wire or group of power wires. Such a condition of zero electromagnetic induction is shown in Fig. 21.

As a third means of reducing the transfer of surge energy from the grounded wire to the power wire, the use of critical damping resistance in the grounded loop has already been mentioned.

XVI—MOVEMENTS OF INDUCED CHARGES ON LINE WIRES COINCIDENT WITH THE MOVEMENTS OF CHARGES IN A CLOUD

So far the assumption has been made that the electrostatic charge on a line starts from a stationary condition at the instant a lightning bolt takes place between the cloud and earth. A stationary charge first collects gradually under the storm cloud. This induced charge is distributed along the line over a distance somewhat greater than the length of cloud, Fig. 22. Coincident with the discharge to earth there is also a collection of the accumulated charge on the line towards one point. This point has been called the bolt peak and is the point on the line nearest to the point on the earth struck by the cloud discharge. In the usual thunder cloud the quantity of electricity in the vertical discharge from the cloud has been gathered from some distance horizontally in the cloud and therefore there will be a corresponding movement of the electrostatic charge on the line as represented in Fig. 23. This preliminary shifting of the charges on the power wires and grounded wires will cause some loss of energy by induction in the grounded loop. If the charge traveling on the line wires can be retarded by means of choke coils, especially those which absorb high-frequency energy, it may be possible to materially decrease the peak of potential on the line wire. This is still an indeterminate condition which should be decided by experimental data on the rapidity of movement and the quantity of electricity which would be concentrated by this particular effect of the lightning discharge. On the side of the retardation by inductance it is evident that only a limited amount of concentrated reactance is permissible on the line.

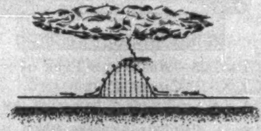


FIG. 23

Concentration of charge on the line at the instant of cloud discharge and coincident with the corresponding movements of charge in the cloud.

If these reactances in the power wires are staggered they will become a help in reducing the potentials of lightning by breaking up the waves. Such a possible effect is shown in Fig. 24 for two parallel wires in which the charge on one is retarded behind the charge on the other and therefore the capacitance of the adjacent wire becomes available in absorbing the charges electrostatically, thereby reducing the potential. Reflections take place at each coil, which again give time for the absorption of the surge energy on the line by the parallel grounded wire. The more the charges can be absorbed on the line the less the amount to reach the apparatus in the stations.

The best type of high-frequency absorbing reactance is the one with distributed resistance between turns. A partially conducting cement is used which serves both as a mechanical support and as an electrical resistance, Fig. 25. As the surge potential piles up on each turn of the coil it forces current through the distributed resistance between turns. Thereby the recoil from stored magnetism is avoided and a part of the surge energy is transformed into heat energy. The steeper the wave front and the higher the frequency the more efficient is the absorption of surge energy. In other words, the more severe the surge, the more it is forced through the resistance.

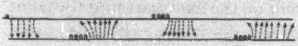


FIG. 24

Illustration of a method of breaking up a traveling wave by retardation, reflection, and absorption by specially designed choke coils placed in staggered position in the three-phase wires. A traveling wave meets the absorber choke coil and three things take place, namely, it is partially absorbed by the shunting resistance from turn to turn, it is partially reflected by the inductance, and it is partially transferred to the adjacent wire by dielectric displacement (as indicated by the arrows). This displaced charge is divided into two parts and one part travels in the opposite direction to the original wave. Thereby a traveling wave is broken up into many parts and dissipated.

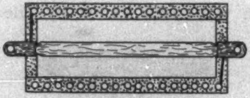


FIG. 25—ABSORBED TYPE OF CHOKE COIL

A choke coil made of bare wires cast in a semi-conducting cement. This gives a distributed leakage which is more effective than shunting the entire coil with a simple resistance. Every turn as it chokes back the surge and raises the potential of it, causes an absorption of its energy by forcing the current through the shunting resistance.

XVII—THE ABSORPTION OF THE TRAVELING WAVES BY THE SUCCESSIVE LOOPS OF THE GROUNDED WIRE

We have just discussed an objectionable feature of the grounded wire in producing a wave train on the power wire and we now come to a condition which is more favorable to the grounded wire. Lightning impulses and all the succeeding traveling waves trains which pass along the power wire must have their electromagnetism looped into every successive grounded wire loop. Thereby each of these grounded loops will have transferred to it a fraction of the energy of the traveling wave and this energy will be more or less absorbed according to the value of the ohmic resistance in the grounded loop. Again, we come to the desirability of having a comparatively high resistance in the grounded loop. This resistance should either be in the earth connection or inserted in series in a wire circuit. In this way the grounded wire will serve as an absorber of traveling waves and should give efficient absorption in all cases except where the induced lightning is near a station and has only a short distance to travel.

If there is no appreciable absorption of energy in the grounded loop, the effect of the grounded loop will be to break up the main traveling impulse into a long wave train of a wave length corresponding to the length of the grounded loop. Thereby a single impulse from a cloud will be transformed into a long train of waves at very high frequency.

XVIII—The Frequency of the Lightning Bolt

So far the assumption is made that the cloud discharge does not oscillate between the cloud and earth. Prof. Elihu Thomson has shown that some parts of the path of discharge in the cloud itself have too much resistance in their paths to permit of a free oscillation. Mr. De Blois' records on an oscillograph (A. I. E. E. Transactions, Vol. XXXIII, 1914, p. 519) have shown this effect. There is, however, low resistance in the main path of the lightning discharge and therefore a possibility of local oscillations between the ends of this conducting streak. Since the length of the conducting streak is comparatively short, its frequency, if it exists, is relatively high, perhaps of the order of 200,000 cycles to a million cycles per second.

Any such oscillation will induce a corresponding oscillation on the transmission line, and will be added to the natural oscillations already discussed. It should be noted that any oscillation induced by an oscillation of a cloud discharge will add surge energy to the power wires at each alternation. The original quantity induced on the line cannot return to the starting point when once freed by the initial action of the cloud discharge. The initial charge takes the form of two traveling waves and there is not much more argument in favor of their return with the oscillation of the cloud discharge than there is that a rifle bullet will return to a gun by the force of the air which rushes into the muzzle after the bullet passes out. The traveling wave, like the rifle bullet, possesses dynamic energy which keeps it traveling once it is set in motion along the line wires.

So each succeeding oscillation of a cloud discharge will start a new oscillation on the line and will thereby produce a wave train which has a greater energy than the original induced charge.

XIX—THE EFFECT OF THE COMBINATION OF LIGHTNING VOLTAGE AND POWER VOLTAGE AT THE INSTANT THE BOUND CHARGE IS SET FREE ON THE LINE

At the instant the cloud discharges to earth these two sets of voltages both appear on the line. The power voltage at one instant has one phase positive, another phase negative, and the third phase at zero potential. If the lightning potential is positive the corresponding quantities of electricity will combine or cancel, leaving an inequality in the voltage of the traveling waves which depart from this point. This subject has been discussed in a previous article by the writer and is of especial interest in the subject of the arcing ground suppressor. It is another factor which adds complication to any exact calculations of what actually takes place during and subsequent to a lightning discharge. This phenomenon may produce a material decrease in the surge potential by causing waves to travel in the three phases one ahead of the other, the stronger holding the weaker one back by electromagnetic induction. As a result it is possible that equally induced charges on the three phases, which have equal tendencies initially to oscillate towards earth may be thrown out of relative location on the longitudinal length of the circuit and thereby produce line to line surges.

XX—HIGH FREQUENCY PRODUCED IN APPARATUS BY TRANSPOSITION OF POWER WIRES

Transpositions of power wires are made with two purposes, at least, in view, namely, first to decrease the induction on parallel lines, and second to prevent shifting of the neutral of the circuit. Our present interest is centered in the second purpose.

If the power wires are hung in a vertical plane the lowest wire will have the greatest capacitance to earth, and the highest wire the least. If there are no transpositions of the phase wires there is a tendency to shift the neutral from the center of the three-phase triangle. If the neutral of the circuit is grounded, this shifting tendency will produce a current at the neutral connection to earth. The current passing to earth will be such as to satisfy the unbalanced capacitances of the phase wires.

If the neutral is not grounded the tendency to shift will cause an actual shifting of the neutral throughout the system. The shifted point will be permanent.

A single phase simplifies the illustration, Fig. 26. To get the direction of shift of the neutral, without mathematical analysis make the capacitance of the lower wire many times greater than the upper wire. Practically this can be done by closing the disconnecting switch on the lower wire and leaving the other disconnecting switch open. As a result the transformer gives the effect of being grounded by the lower wire. The capacitance of the lower wire is so great as compared to the capacitance of the coils of the transformer that the potential of the connected side is reduced sensibly to zero.

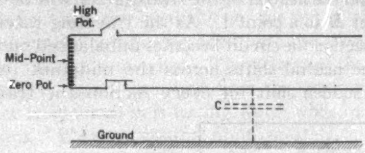


FIG. 26

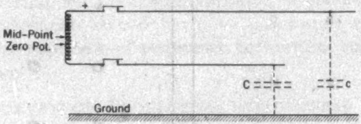


FIG. 27

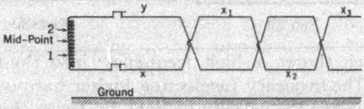


FIG. 28

Now, if the upper line wire is connected to the transformer, the two sides will be more nearly balanced but the lower wire will still have the greater capacitance and therefore the neutral will remain shifted from the midpoint of the transformer coils as indicated in Fig. 27.

Incidentally it might be noted in passing that the arcing at the switch contact in opening on one line wire alone causes rapid shifting of potential in the transformer at every break of the arc. If the length of line is such as to resonate with the natural frequency of the transformer coils, and especially if the transformer coils are not designed to break up the surges into several different frequencies, it is possible to get local resonance in the transformer coils. Such resonance will produce high voltages.

Our problem is the production of high frequencies, especially at the time of switching, not by arcing, but by the transposition of the phases along the line. Fig. 28 shows a transformer being closed on a transposed line. In the first section wire *x* is the lower one and the neutral of the transformer will be shifted from the midpoint *M* to a point 1. As the traveling wave runs along the second section the circuit becomes unbalanced on the opposite side and the neutral shifts across the midpoint to a point 2. There is a sudden shift for every section the traveling wave passes, which throws a high frequency into the transformer windings. The frequency (neglecting higher harmonics) can be found by dividing the velocity of light by twice the number of miles per transposition. For example, if the line is transposed every five miles, the frequency produced by closing a switch on to this dead line will be 18,300 cycles per second.

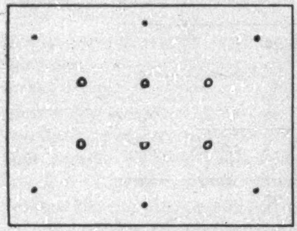


FIG. 29

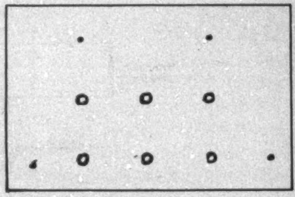


FIG. 30

$$\left[\text{(183,000 miles per second)} \div 2 \times 5 = 18{,}300 \right]$$

At 60 cycles or any frequency low as compared to the natural frequency of the line the successive sections of transposition cancel the unbalanced currents and as a result there will be no shifting of the neutral. There can be no such cancellation for a traveling wave because the charging currents do not flow to the several sections simultaneously, but successively.

The degree of unbalancing depends upon the relation of the capacitance of the coils of the transformer to the difference in capacitances of the line wires. As an example, the following data are used: Two line wires No. 000 (one cm. diameter) are vertically hung and transposed every five miles. The upper wire is 66 ft. high (2000 cm.) and the lower wire 40 ft. high (1210 cm.) The capacitance of the upper wire to earth is 10.2 milli-mf. per mile (0.0557 statfarad per cm.) and of the lower wire 10.55 milli-mf. per mile (0.0590 statfarad per cm.)

If the quantities emanating from each wire are assumed to be equal, the potential of the upper wire will be 7 per cent greater than the lower wire. If, on the other hand, the potentials are assumed to be equal the quantity on the lower wire will be 5 per cent greater than the quantity on the upper wire. If the neutral of the circuit is not grounded both the charges and the potentials will change somewhat. The voltage of the upper wire will differ by less than 7 per cent from the lower wire. Since this difference is so small it is hardly worth while to make careful calculations. We may assume approximately that the shifting of neutral is about 4 per cent of the potential of one wire. It is evident that such a slight variation in potential even at high frequencies can do no harm to transformer coils except perhaps in the rare case of resonance between the coils and this high frequency.

GENERAL SURVEY OF PROTECTION BY OVERHEAD GROUNDED WIRE

It is impossible to make definite recommendations which will cover all conditions of transmission circuits. There is much territory where lightning is not prevalent and therefore the expense of the overhead wire may well be avoided. There are also cases where spurs of circuits are carried out to small consumers where the financial returns do not warrant the expense. If such a circuit, when damaged, can be made to free itself from the main circuit without a general interruption, the use of a grounded wire can be questioned. There may be still another case where, theoretically at least, the overhead wire may not be necessary. This condition will occur when the insulation of the transmission line is so high that an induced stroke cannot flash over the insulators. In other words, the insulators cannot be flashed over except by a direct stroke. With the suspension-type insulators and the tower carried well above the insulators the parallel grounded wire would then be of no particular value. What the dielectric strength of such an insulator must be is not known.

In the majority of transmission circuits, however, the problem is rather of the nature of how many overhead grounded wires to use and where to place them to get the greatest advantage. Certain mechanical conditions will limit the freedom of choice of location. For example, with the usual suspension type of construction it may be unwise to install overhead grounded wires in the same horizontal plane as the power wires, due to the chances of grounding by side swinging. At any rate, the wider tower would be materially more expensive. Under such conditions the overhead wires would naturally be strung either above or below.

In the case, however, of pin-type construction the grounded wires may be placed laterally as well as above the power wires.

Various locations of grounded wires are shown in Figs. 29, 30, 31, 32, and 33.

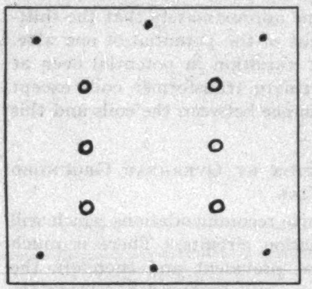


FIG. 31

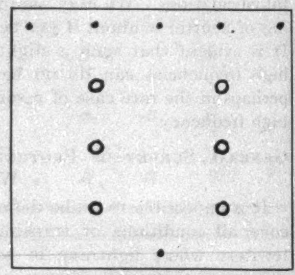


FIG. 32

Fig. 29 shows two parallel circuits of six wires arranged in horizontal formation and six grounded wires separated as widely as possible from each other and yet as near to the power wires as mechanical clearance will permit. The grounded wires are arranged in pairs symmetrically so as to decrease the electromagnetic induction. The two outside lower wires might be raised to the same position as the corresponding one in Fig. 30 without making much difference in the protective value, or the two upper outside wires might be lowered on each side without making a very great difference in the protection. Mechanical conditions of support will be the criterion. The simple rule is to space the overhead grounded wires as far from each other as convenient, but as near to the power wires as is safe.

Fig. 30 shows a desirable location for four grounded wires on the same type of circuit as Fig. 29.

Fig. 31 shows a distribution of six grounded wires for two three-phase circuits vertically hung. In some cases it may be desirable to keep the grounded wires within the same width as the two circuits.

Fig. 32 shows another disposition of the six grounded wires which is not so good from the electromagnetic standpoint but which is somewhat better from an electrostatic standpoint. It has already been shown that the lower wires of the vertically hung circuits are greatly protected by their lesser height above earth and therefore they do not need the presence of grounded wires as much as the upper power wires.

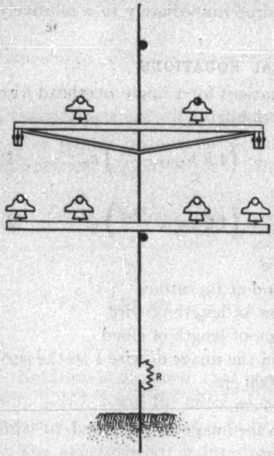


FIG. 33

Fig. 33 shows a desirable distribution of four grounded wires where non-grounded pins on the insulators are used. To preserve the insulation afforded by the wooden cross-arm the metallic connections of the laterally grounded wires are carried free of the cross-arm, in fact, long metal braces might be used in this case. At one point in the circuit is shown a series resistance to bring the total resistance in the grounded loop up to a value at least equal to one-fifth of the critical damping resistance.

From an electrical standpoint grounded wires of small diameter can be used. From a mechanical standpoint the size of the wire is dictated by the length of span. From calculation of loading of the wire under sleety conditions the practise calls for about a 3/8-in. (9.5 mm.) stranded Siemens-Martin steel wire for a span of 600 ft. (182 m.), $\frac{1}{4}$-in. (6.3 mm.) for a span of about 250 ft. (76 m.), and the ordinary telegraph wire for spans of about 100 ft. (30. m.).

The cost of the $\frac{3}{8}$-in. (9.5 mm.) steel wire will vary according to the cost of the metal and the cost of stringing, being usually somewhat greater than $100 per mile rather than less, although $100 per mile is a convenient figure to use for comparisons. The total cost of electrical circuits, including the towers, varies from $2000 to $12,000 per mile. Each overhead grounded wire adds to the cost from 5 per cent to 1 per cent of the cost of a line. Since the use of several grounded wires gives such a large percentage of protection against lightning strokes in most cases they are justified. If line protection could be made so thorough as to do away with large installations of steam auxiliaries in local substations the cost of parallel grounded wires would drop immediately to a relatively insignificant figure.

MATHEMATICAL EQUATIONS

Following are the general equations for a single overhead wire and a parallel cylindrical storm cloud:

$$V_1 = \left(4.6 \log_{10} \frac{m_{11}}{r_1}\right) q_1 + \left(4.6 \log_{10} \frac{m_{c1}}{r_{c1}}\right) q_c \qquad (1)$$

$$V_c = \left(4.6 \log_{10} \frac{m_{1c}}{r_{1c}}\right) q_1 + \left(4.6 \log_{10} \frac{m_{cc}}{r_c}\right) q_c \qquad (2)$$

Where V_1 = potential of the wire

V_c = potential of the cloud at its surface

q_1 = statcoulombs per cm. of length of wire

q_c = statcoulombs per cm. of length of cloud

m_{11} = distance in cm. from the image of wire 1 to the surface of wire 1 = 2000 cm.

r_1 = radius of wire 1 = .5 cm.

$m_{c1} = m_{1c}$ = distance from the image of the cloud to wire 1 = 56,000 cm.

$r_{c1} = r_{1c}$ = distance from the apex of charge in the cloud to wire 1 = 54,000 cm.

m_{cc} = distance from the image of the cloud to the surface of the cloud = 100,000 cm.

r_c = distance from the apex of the cloud charge to the lower surface of the cloud = 10,000 cm.

On substituting these values, equations **3** and **4** are obtained:

$$V_1 = 16.6\, q_1 + .0727\, q_c = 0, \qquad q_c = 5700 \qquad (3)$$

$$V_c = .0727\, q_1 + 4.6\, q_c = V_c \qquad V_c = 26{,}200 \qquad (4)$$

For two parallel wires in a horizontal plane, both grounded, the quantities are found from the following relations where 414.7 is the potential of the undisturbed field at 1000 cm. above the earth.

$$V_1 = 0 = 16.6\,q_1 + 6.0\,q_2 - 414.7 \qquad (5)$$

$$V_2 = 0 = 6.0\,q_1 + 16.6\,q_2 - 414.7 \qquad (6)$$

$$q_1 = q_2 = 18.36 \text{ statcoulombs per centimeter} \qquad (7)$$

$$\text{Electrostatic energy} = \frac{1}{2}\,q_1\,V_1 = \frac{1}{2} \times 18.36 \times 414.7$$

$$= 3805 \text{ statjoules per cm.} \qquad (8)$$

For comparison of one of two wires to one wire alone:

$$\text{(One wire only) Energy} = \frac{1}{2} \times 25 \times 414.7$$

$$= 5180 \text{ statjoules per cm.} \qquad (9)$$

Capacitance of one of two wires to ground = 0.0443 statfarad per cm. **(10)**

Capacitance of one wire to ground = 0.0603 statfarad per cm **(11)**

The general relations of potential in statvolts and quantity in statcoulombs per cm. length of wire are given below:

$$V_1 = \left(4.6 \log_{10} \frac{m_{11}}{r_1}\right) q_1 + \left(4.6 \log_{10} \frac{m_{21}}{r_{21}}\right) q_2 - (\text{gradient} \times \text{height } (1)) \qquad (12)$$

$$V_2 = \left(4.6 \log_{10} \frac{m_{12}}{r_{12}}\right) q_1 + \left(4.6 \log_{10} \frac{m_{22}}{r_2}\right) q_2 - (\text{gradient} \times \text{height } (2)) \qquad (13)$$

Notation is similar to that of equations **1** and **2**. The second wire is No. 2 and the effect of the cloud is simplified to the expression, "gradient × height of wire."

The equations for induced quantity on 5 wires (4 grouped around one, height of 1000 cm., spacing 100 cm., see Fig. 11 in text) are as follows:

$$V_1 = 0 = 16.6\,q_1 + 12.0\,q_2 + 6.1\,q_3 + 5.9\,q_5 - 414.7 \qquad (14)$$

$$V_2 = 0 = 6.0\,q_1 + 21.2\,q_2 + 5.4\,q_3 + 5.2\,q_5 - 414.7 \qquad (15)$$

$$V_3 = 0 = 6.1\,q_1 + 10.8\,q_2 + 16.76\,q_3 + 4.6\,q_5 - 455.8 \qquad (16)$$

$$V_5 = 0 = 5.9\,q_1 + 10.4\,q_2 + 4.6\,q_3 + 16.36\,q_5 - 373.0 \qquad (17)$$

$q_1 = 8.45$, $q_2 = q_4 = 11.45$, $q_3 = 14.4$, and $q_5 = 8.4$.

To get the protection and potential ratio due to the use of a parallel grounded wire:

Symbolical solution for potential ratios of two wires in a horizontal plane, one of which is a parallel grounded wire. The initial induction is given by equations **12** and **13**, or simplified:

$$V_1 = 0 = a\,q_1 + b\,q_2 - (\text{gradient} \times \text{height of wires}) \qquad \textbf{(18)}$$

$$V_2 = 0 = b\,q_1 + d\,q_2 - (\text{gradient} \times \text{height of wires}) \qquad \textbf{(19)}$$

Let k be the undisturbed potential at the height of the wires

Then

$$q_1 = \frac{d - b}{ad - b^2}\,k, \qquad q_2 = \frac{a - b}{ad - b^2}\,k \qquad \textbf{(20)}$$

After the cloud discharges the charge on wire 1, the grounded wire, will pass to earth and wire 1 will take an induced charge q^1.

$$V_1 = 0 = -\,a\,q' + b\,q_2 \quad \text{whence } q' = \frac{b}{a}\,q_2 \qquad \textbf{(21)}$$

Substituting this in the new equation for the potential of wire 2

$$V_2 = -\,b\,q' + d\,q_2 = \left(d - \frac{b^2}{a}\right) q_2 \qquad \textbf{(22)}$$

Substituting the value of quantity on wire 2 from equation **20** gives for the potential of the power wire:

$$V_2 = \frac{ad - b^2}{a} \quad \frac{a - b}{ad - b^2}\,k = \frac{a - b}{a}\,k \qquad \textbf{(23)}$$

The potential of wire 2 without protection of wire 1 is

$$V_2' = k, \text{ therefore} \qquad \textbf{(24)}$$

$$\frac{V_2 \text{ protected}}{V_2' \text{ unprotected}} = \frac{a - b}{a} \qquad \textbf{(25)}$$

In which these coefficients are the same as given in equations **12** and **13**

$$a = 4.6 \log_{10} \frac{m_{11}}{r_1} \text{ and } b = 4.6 \log_{10} \frac{m_{12}}{r_{12}} \qquad \textbf{(26) and (27)}$$

$$d = 4.6 \log_{10} \frac{m_{22}}{r_2} \qquad \textbf{(28)}$$

The protection is independent of the coefficient (d) which depends on the size of the power wire.

If the grounded wire is above the power wire the ratio would be decreased in proportion to the percentage of height, then

$$\frac{V_2 \text{ protected}}{V_2' \text{ unprotected}} = \frac{a - b}{a} \times \frac{\text{height of power wire}}{\text{height of gr. wire}} \qquad \textbf{(28a)}$$

If, on the other hand, the grounded wire is below, the fraction containing the heights is inverted.

Protection afforded by two grounded wires with a power wire symmetrically placed cetween them, all three wires in a horizontal plane. The outside wires, No. 2 and 3, will have equal quantities of electricity induced on them. The general equations are:

$$V_1 = a\,q_1 + b\,q_2 + b\,q_3 + k \qquad \textbf{(29)}$$

$$V_2 = b\,q_1 + c\,q_2 + d\,q_3 + k \qquad \textbf{(30)}$$

With the wires at zero potential and the cloud charge negative,

$$V_1 = 0 = a\,q_1 + 2\,b\,q_2 - k \qquad \textbf{(31)}$$

$$V_2 = 0 = b\,q_1 + (c + d)\,q_2 - k \qquad \textbf{(32)}$$

$$q_1 = \frac{c + d - 2b}{a\,(c + d) - 2b^2}\,k \qquad \textbf{(33)}$$

Immediately after the lightning discharges

$$V_2 = 0 = b\,q_1 - (c + d)\,q',\ q' = \frac{b}{c + d}\,q_1 \qquad \textbf{(34)}$$

$$V_1 = a\,q_1 + 2\,b\,q' = \frac{a\,(c + d) + 2b^2}{c + d}\,q_1$$

$$= \left(1 - \frac{2\,b}{c + d}\right)k \qquad \textbf{(35)}$$

As before (k) disappears in the potential ratio which becomes

$$\left(1 - \frac{2b}{c + d}\right)$$

$$\text{The protection} = \frac{2\,b}{c + d} \qquad \textbf{(36)}$$

If instead ,of taking the two grounded wires equally spaced from the power wire, they should have been unequally spaced, then $2b$ becomes two separate factors, say $(b + f)$, and the protection from two parallel grounded wires becomes

$$\text{protection} = \frac{b + f}{c + d} \tag{37}$$

$$\text{Where } b = 4.6 \log_{10} \frac{m_{21}}{r_{21}}, \left\{ \begin{array}{l} m_{21} = \text{image 2 to wire 1} \\ r_{21} = \text{spacing wires 2 and 1} \end{array} \right\} \tag{38}$$

$$f = 4.6 \log_{10} \frac{m_{31}}{r_{31}}, \left\{ \begin{array}{l} m_{31} = \text{image 3 to wire 1} \\ r_{31} = \text{spacing wires 3 and 1} \end{array} \right\} \tag{39}$$

$$c = 4.6 \log_{10} \frac{m_{22}}{r_{2}}, \left\{ \begin{array}{l} m_{22} = \text{image 2 to wire 2} \\ r_{2} = \text{radius} \end{array} \right\} \tag{40}$$

$$d = 4.6 \log_{10} \frac{m_{32}}{r_{32}}, \left\{ \begin{array}{l} m_{32} = \text{image 3 to wire 2} \\ r_{32} = \text{spacing wires 3 and 2} \end{array} \right\} \tag{41}$$

Since the grounded wires are assumed to be the same diameter and the same height $\frac{m_{22}}{r_2} = \frac{m_{33}}{r_3}$

DISCUSSION ON "THEORY OF PARALLEL GROUNDED WIRES AND PRODUCTION OF HIGH FREQUENCY IN TRANSMISSION LINES" (CREIGHTON), CLEVELAND, OHIO, JUNE 29, 1916.

Harold S. Osborne: In considering any circuit which uses the ground as part of the electric circuit, we are forced to take account of a factor which in the present state of the art is to a considerable extent unknown, that is the property of the ground itself. The ground is not a perfect conductor, and in a great many instances in which the ground is used as a part of the circuit, the effect of the resistance of the ground is very considerable.

In dealing with currents of a few hundred or a few thousand cycles, we have found that as to electrostatic effects, the resistance of the ground usually has but slight effect. The determination of what the equivalent level of the ground is, is sometimes difficult. For example, a row of trees may have a considerable electrostatic effect, and would be very difficult to take account of in mathematical work. In electromagnetic effects, the resistance of the ground is, for currents of the frequencies of which I have spoken, ordinarily very considerable. We have found in some cases that a grounded circuit produces the same effect as though the return current were concentrated at a point a thousand feet below the surface of the earth, and in some cases a considerably greater distance, and I would be very much interested if Mr. Creighton can give us any information regarding the effects of the ground at these very high frequencies which he is discussing.

The other point I had in mind is an effect of the use of overhead grounded wires of which the author does not speak—the overhead grounded wires not only tend to protect the power lines from induced charges from clouds, but also tend to protect the circuits paralleling the power lines from charges induced by the power circuit. This effect is very considerable in some cases, and I am sure that telephone engineers should be pleased that Mr. Creighton is advocating their more extended use.

N. S. Diamant: I think it is well in connection with this paper to call attention to the advantages of investigating graphically electrostatic effects of ground wires, at least in the simple cases; the advantage of the graphical method is its simplicity and especially the fact that it gives a picture of the electrostatic stresses existing in the space near the ground and transmission wires.

From the nature of the subject, I think it is a serious defect not to have included in the paper references to previous work and to detailed mathematical and graphical solutions. The fundamentals on which the treatment of the subject is based are given in the monumental works of Maxwell. However, without going to original sources it would have added greatly to the value and usefulness of the paper to have a few references; even if the author used no references whatsoever, it would not have been as difficult for him to look up some, as it will be for any reader who may desire further details.

As Mr. Creighton has emphasized there are important assumptions to be made which are not unassailable and on which differences of opinion may exist. The results of this paper depend on these assumptions which Mr. Creighton has so clearly brought out. Now, references, no matter how incomplete, would have allowed us to compare some of the author's assumptions and results with those of others.

John B. Taylor: I must confess to being somewhat confused in following this paper, through the use of some of the terms. For instance, when we are discussing periods of time as brief as a millionth of a second, what is the interpretation to be put on such words as "instantly" and "suddenly." I judge Mr. Creighton wants us to assume that a charge accumulates in a cloud gradually through moisture condensation or other atmospheric condition, and that equally gradually the ground wire and the conductors of the line accumulate charges by induction from the cloud. Then "suddenly" without regard to time, it is assumed that the charge on the cloud, disappears in a lightning stroke, leaving the charge on ground wire to oscillate at its own natural period as determined by the conditions of the circuit,—distance between earth connection and the inductance and capacity involved.

A different state of affairs seems more consistent with his estimated length of lightning stroke as one mile. How is it possible to be rid of the charge on the cloud through a stroke a mile long in a time negligible compared with the time of oscillation in the overhead ground-wire circuit, which is given, in a 500-foot span, in the order of two million cycles per second.

The transfer of the cloud charge over a mile will take, in round figures, ten times as long as for the overhead wire charge to reach earth through the connection provided at 500-foot intervals. From this the release of the induced charge on the ground wire should follow the cloud discharge and be practically a periodic, instead of setting up oscillations of the order of millions of cycles.

In discussing the early use of overhead ground wires, Mr. Creighton may have overlooked the long established practise of the American Telephone & Telegraph Company. The "zero" wire on the tops of the poles served for lightning protection, mechanical stability, and convenience in testing. Mr. Creighton points out that a small wire is almost as effective as a large wire, as regards its electrostatic effect, but mechanical strength and ability to discharge heavy strokes without fusing are important factors. In some early installations poor material and flimsy construction gave more trouble than was prevented. There was a time when ground wires were in disfavor, but they have come into favor again, only after recognition of the need for good mechanical construction.

John B. Whitehead: It is interesting to remember that ever since the days of Benjamin Franklin, scientists, physicists and engineers have studied lightning phenomena, but no satisfactory explanation or theory has resulted. It is impossible, of course, to control the conditions in the natural case, and hence experience is limited to inadequate laboratory studies. Therefore it seems to me that it is quite proper to build up assumptions which come as near to actual conditions as our existing theories indicate, and then to compare the results following from them with the natural case.

Several years ago a paper was read before the Institute by Mr. J. P. Jackson, in which he made an effort to plot the equipotential surfaces of a transmission line with ground wires upon the towers. The surface of zero or ground potential, was shown to have different shapes in accordance with the different positions of the ground wire. The whole question reverts of course to Faraday's original proposition, which has been justified by experience in a hundred ways, that if you want to protect anything from lightning or from electrostatic influences surround it by a grounded cage. The grounded wire is simply a small approach to that condition, and therefore taking the conditions Mr. Creighton outlined in his abstract, it is perfectly natural that the nearer you put a grounded wire to the transmission wire just so much more nearly do you give it a grounded screen.

I question the correctness of one of the conclusions, namely that the grounded wire placed below the power wire should give it approximately as much protection as when the grounded wire is placed above it. Naturally, there would be some, but I think the difference should be quite considerable for all but the smallest distances of separation. Otherwise, the conclusions are in accord with the conception that the grounded wire, is simply an approximation to a grounded cage.

The author questions whether a lightning rod should be pointed, since when the corona starts from a point it is equivalent to making the wire blunt ended. My conception of the point of the lightning rod is that it gradually dissipates the charge as the potential rises by the discharge from its points, and consequently tends to keep down the potential. I should, therefore, question whether a blunt point would serve so well as a sharp point.

L. W. Chubb: The author speaks of the peaking of the charge, illustrated in Fig. 8, causing a displaced negative charge which forces a charge in the windings of the apparatus in an undesirable way. I understand that this menace only exists for the ungrounded system.

E. E. F. Creighton: Yes.

L. W. Chubb: Mr. Taylor has called attention to the relative time constants of the short line sections and the long lightning path, precluding the possibility of propagated wave trains and the more probable existence of sloping wave fronts. This is, I think, an important point and the analysis of lightning phenomena should be made assuming only factors of the proper order of magnitude.

In Fig. 14 Mr. Creighton has shown the parallel ground wire divided into short sections by the grounding wires, and each having an electrostatic capacitance to ground. At the time of discharge from cloud the freed charge in each section will divide and pass out the grounding wires as shown. The currents in the adjacent sections will induce in the power line traveling waves in opposite directions, which will result in standing waves. If the induced waves in the power line are nearly in phase there will be a rather complete cancellation of the waves and a falling off in amplitude along the line as it passes outside of the influence of the cloud. This cancelling effect and the damping in the circuits would seem to be enough to limit the wave trains beyond the influence of the cloud to a rather insignificant amplitude. There is also some doubt in my mind whether the released charge in the section of the ground wire will oscillate, because the capacitance is not concentrated as shown in the figure. The section has distributed capacitance and inductance. If the distributed constants of the section of the ground wire do prevent the propagation of wave trains in the power line, the standing waves will not exist and the bad after effects of the ground wire would be reduced to a very sloping wave front of much less amplitude than if the ground wire were not present.

In several places in the paper the author, in pointing out the inductive effects of the ground wire on the power wire, speaks of the sudden change in capacitance to the line. Capacitance is an invariable physical constant and I cannot see how a change in capacitance takes place during the transient.

E. E. F. Creighton: I am unable to give Mr. Osborne any experimental information on the distribution of high-frequency currents in the ground. I am glad Mr. Osborne added another use of the overhead grounded wires which I had overlooked.

Referring to Mr. Diamant's request for a bibliography, I have to confess that I did not make one and in fact did not attempt to look up all the references. The mathematical equations, as originally given by Maxwell and Heavyside are available to those who have the volumes. These I have not referred to for many years. The work by Heavyside will be found in one of his two volumes of "Electrical Papers."

Referring to Mr. Taylor's comments—I endeavored to simplify this matter by considering only one variable at a time. The neglected factors are, I believe, stated in the foot note. The words "instantly" and "suddenly" then refer in an indefinite way to the period of time corresponding to the length of charge in the constants of a circuit. In reading the paper it should be kept in mind that in the beginning all factors that could be set aside were neglected and subsequently each one of these was considered, although they were not all combined, as it would make the subject too complex.

Referring to Dr. Whitehead's skepticism on the protection given by an under-hung wire—I can only recommend to him that he make the calculation to be convinced.

Referring to the last paragraph in Mr. Chubb's discussion—it is impossible to come to any definite understanding because of the several different definitions given for capacitance. If one defines capacitance as the quantity per unit difference of potential, then Mr. Chubb's conception of the invariable physical constants will hold only when there are two electrodes, namely one positive and one negative. We often think of capacitance as certain dimensions, as is always true in a single condenser but when there are three or more electrodes then capacitance is determined not only by the physical relations but also by the relative potentials of the conductors. I have worked out many examples to prove this statement. The calculations are too long to include in this discussion. This paper was shortened more than 50 per cent by curtailing the mathematical work and calculations. I can hardly hope to have deleted this material judiciously in every case although I hope I have put enough mathematical work at the end of the paper to suffice for the understanding of the equations used.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 30, 1916.

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SUGGESTIONS FOR ELECTRICAL RESEARCH IN ENGINEERING COLLEGES

BY V. KARAPETOFF

ABSTRACT OF PAPER

The primary object of the paper is to present a list of topics in electrical engineering suitable for thesis, research, and advanced study. A plea is made for systematic research, each college specializing year after year in only a few topics for advanced investigation. The author suggests that the Educational Committee of the Institute become a central place for information and a stimulus in applied electrical research, cooperating with engineering colleges and with individual inventors and investigators.

Various types of investigations are enumerated, such as invention, experimental study, theoretical study, library search, and compilation of data. Some advice is given the young investigator as to how to proceed in the most efficient way and to avoid a disappointment.

"WHAT topic shall I choose for my required thesis?" This is a question that will sound familiar to a teacher in electrical engineering. Sometimes the students puts the question in this way: "I have some spare time and should like to do research work; what would you suggest for a subject?" Again, once in a while a young practising engineer writes that he does not wish to become "rusty" and asks that a subject be suggested for systematic study in the evenings. Truth forbids the statement that such inquiries come often enough to be burdensome; nevertheless the writer found it convenient some years ago to compile "A List of Electrical Subjects for Thesis, Research and Advanced Study," as a ready reference in answering such inquiries. This list was privately printed in 1909 and has been used since by a number of the author's colleagues in various engineering colleges.*

A revised and augmented list is now offered to the profession in the hope that it may prove useful and stimulating to students, to teachers, and to engineers who are interested in research, invention, and advanced study in electrical engineering.

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*For a similar list of topics in mechanical engineering see H. Wade Hibbard, "Thesis Directions for Students," Proceedings of the Society for the Promotion of Engineering Education, Vol. 21 (1913) p. 129.

The author also recommends that the Educational Committee of the Institute revise this list from time to time and keep it up to date, soliciting additional suggestions from various technical committees, from prominent practising engineers and from teachers. In this manner the Educational Committee would in time become a source of information and stimulus for organized electrical research.

Anyone who follows European electrical periodicals will agree that this country is behind Germany and England in the invention of new types of electrical machinery and apparatus, in the discovery of new electrical phenomena, and in the development of working theories and numerical relations needed in our profession. Whatever the causes of our backwardness, we must find a remedy for it, and the most important first step is to systematize and organize research.

The American Institute of Electrical Engineers has not limited itself in the past merely to recording the progress of the art and the opinions of its members. Through its committees and representatives the Institute has participated in the solution of a number of important national and international problems, and it has never failed to take an active interest in activities by which it was able to render important service to the profession and to the nation.

The promotion of organized research in engineering and the encouragement of young men to train themselves in the art of invention is at present an important national problem, if we are to rank with the leading European nations and to be independent of them in times of need. The author has emphasized elsewhere more in detail the importance of *systematic* research and of encouraging the art of invention among young engineers.* The national engineering societies are naturally called upon to lead in this movement, and the American Institute of Electrical Engineers ought to do its share. In fact, one of the principal objects of the Institute, according to its

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*See his paper entitled " What has Engineering Education contributed to Scientific Progress and Invention," presented at the second Pan-American Scientific Congress in Washington, D. C., on Dec. 31, 1915, and published in the Bulletin of the Society for the Promotion of Engineering Education, April 1916, p. 597. See also J. A. Fleming, "Organization of Scientific Research," *The Electrician*, (London), Feb. 18, 1916.

constitution, is "the advancement of the theory and practise of electrical engineering and of the allied arts and sciences."

The Educational Committee of the Institute could well carry on this work if some of its members were selected with this purpose in view, and if it could arrange for cooperation with the other technical committees. This would be a distinct field of activity closely connected with the rest of the work of the Institute, and at a safe distance from the work of special educational societies, especially the Society for the Promotion of Engineering Education. This new activity of the Educational Committee of the Institute might be carried on as follows:

1. The Educational Committee could announce in the PROCEEDINGS and by letter to the electrical departments of the technical schools in North, Central, and South America that it is prepared to assist the students and young engineers by suggesting topics for research, invention, and advanced or special study.

2. The Educational Committee could regularly collect and publish suggestions as to timely topics for research from the technical committees of the Institute, from manufacturing and operating concerns, testing laboratories, consulting engineers, prominent scholars, etc.

3. The Educational Committee could collect information as to the facilities for research available in different schools, and the problems already solved or under investigation. The principal schools might be induced to conduct certain researches in cooperation, rather than to duplicate work. Each school ought to specialize in research along a few definite lines year after year, in accordance with the facilities available and the relation to the local industries. In this manner valuable results could be achieved, whereas now the attempts are mostly sporadic, leading nowhere.*

4. The principal results of research might be published regularly in abstract in the PROCEEDINGS, and thus made of general use, where now they are simply filed in college libraries.

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*Perhaps the most instructive case of systematic research carried on through many years was that at the Elektrotechnisches Institut in Karlsruhe, under the inspired guidance of the late Engelbert Arnold (1856-1911). As a result of this work we have several volumes of the most accurate and useful information on dynamo-electric machinery and numerous valuable inventions; while scores of Arnold's former students all over the world, are prominent as inventors, investigators, designers, and scholars. In this country Professor Harris J. Ryan with his students has carried on investigations on dielectric stresses for years with splendid results.

5. The Educational Committee from time to time should publish in the PROCEEDINGS a brief account of the most important progress in apparatus, methods of measurement, mathematical relations, etc. In these accounts emphasis should be placed upon the method of attack, logical reasoning, patience of the inventor or the investigator, the importance of a clear knowledge of physics, mathematics, mechanics, and chemistry, and in general all such facts as may encourage young investigators and help them in their own research.

6. The Institute might announce each year one or more prizes and medals for the best improvement in apparatus, measurement of some difficult quantity, the best theoretical investigation, etc. These prizes need not be over $50 to $100 each, and the money can be easily appropriated out of the general expense fund of the Institute. Prizes might also be announced for the solution of definite problems of special importance in manufacturing and manufacturers might be induced to furnish money for them.

7. The Institute could help both the electrical industry and the colleges by inducing larger electrical concerns to maintain industrial scholarships in engineering colleges that are prepared for the work. Such scholarships have proved very useful in chemical industry, and in the manufacture of cement, steel, etc.

8. The Institute might pave the way and lend its influence towards the foundation of a National Institute for Electrical Research, or even a National Institute for Engineering Research, similar to some existing institutes for medical research.

GENERAL REMARKS

1. The list furnished is by no means complete or exhaustive and is primarily intended to be suggestive. It would of course be out of the question to write out in detail the purpose and the program of every possible investigation in electrical engineering. The important preliminaries to almost any bit of research are to find out the present status of the problem, to formulate what is needed, and to devise the means for carrying on the investigation. Having selected a general topic the student should make a search in the literature of the subject, consult his instructors, and if necessary take the matter up with outside specialists.

2. The topics are suggested in general terms only, because it is not supposed that a beginner would use the list. If neither the student nor his teachers know anything about the present

status of a certain topic, it is hardly likely or even advisable that the student should take it for his thesis. He needs an elementary text-book on the subject. If, however, at least one of them knows something about the particular topic, its mention in the list will be sufficiently suggestive, and will recall to his mind certain definite problems to be investigated, and he will know where to go for some first-hand information on the subject.

3. Each technical college will find it more effective and more useful from an educational point of view to induce successive students to continue each other's investigations for a term of years until definite results have been achieved. The college can then afford to invest a considerable sum of money in apparatus and will develop real experts among its faculty who supervise this research. With a proper selection of a few topics this policy would in a few years lead to the formation of a valuable specialized experiment station.

4. As far as possible, only subjects of vital interest have been selected for the list, although the author does not believe that the immediate applicability of the results is of prime importance. What counts is the ability to size up a situation; to obtain the necessary information; to concentrate one's whole attention and interest on a problem, and to get definite results. Facts and relations that are of no practical use today, may become very important presently.

5. Much valuable work can be accomplished by colleges and their advanced students through exercising a wise foresight as to future developments in the electrical industry. Often manufacturers feel disinclined to experiment on subjects whose commercial usefulness seems remote, and here is where a college can blaze the way, clear the situation, perform the first preliminary experiments and bring the results to the attention of those who may continue the work on a larger scale and with more accurate means.

6. A résumé of the present situation is needed in most of the important topics for research. Sometimes a student without much imagination but with plenty of patience may be utilized for this preliminary work; he may thus become a useful contributor to the solution of a problem where he would have failed if allowed to undertake an original investigation. It is earnestly urged that students and others interested in the progress of our profession do more of this kind of work, describing in a connected and critical manner what has been done, how it was done, where the information is to be found, and what remains to be done.

Such information freely published in magazines and transactions would not only serve as a powerful stimulus for research, but would relieve able investigators and inventors of a great burden.

PRINCIPAL TYPES OF INVESTIGATIONS

(a) *Invention or improvement* in apparatus, in connections, in materials, in methods of manufacture, etc. If possible, always take an investigation of this kind, because the progress of engineering art depends essentially upon invention.

(b) *Search in the patent records of the United States and foreign countries* with the view of determining the state of the art in a particular subject or branch of industry. Such a search often saves a great amount of labor, expense, and bitter disappointment later on. Moreover, a thorough knowledge of the combinations and means used by other inventors sometimes suggests one of the remaining combinations not covered by patents, or an improvement in the preceding inventions. If students and young engineers would do more of this class of work and less promiscuous inventing, we would have fewer annoying and disappointed inventors, and more inventions of real value.

(c) *An experimental investigation* of some device or group of devices, a material, a proccss, etc., to determine the effect of certain factors, for future guidance.

(d) *A theoretical investigation* of some relationship or phenomenon, with the view to explaining or generalizing certain observed facts; also to predict performance, to enable the designer to proportion a piece of apparatus, to avoid some harmful effect in operation, or to take fuller advantage of some beneficial effect.

(e) *Compilative* or semi-compilative work, such as systematization of notation or nomenclature; comparison of theories, experiments or data of various investigators: unification and simplification of procedure in design or in other computations; preparation of tables, curves, formulas, etc., for a particular purpose; bilbiography of a given topic, etc.

ADVICE TO THE YOUNG INVESTIGATOR

1. One who hopes to succeed in invention or research must possess persistence, accuracy, imagination, resourcefulness, good general education (so as to borrow methods from other branches of science) and in addition some special knowledge or skill directly pertaining to his problem. It may be experimental skill, dexterity with tools, mathematical ability, knowledge of foreign languages,

etc. Often an attempted research ends in failure not because of alleged external difficulties but because the student selected the wrong kind of problem; for instance, one requiring experimental ability, when his strong point is library research. An insufficient knowledge of the fundamentals of one's profession often results in a failure in research, though it is sometimes difficult to convince the student of the connection between the two.

2. Before taking up a piece of special research ask yourself if the same time could not be more profitably spent in a study of some more general topic in electrical engineering. For example, would you spend, say, half a year in experimental research of the effect of wave-form of the applied voltage upon the core loss in a transformer, or would it be more useful for yourself to put the same time in a study of books and articles on transformers in general, their theory, construction, design, connections, etc.? This question no one but yourself can answer.

3. Remember that in practically every case you expect to continue the work of others; therefore be particularly careful to find out what has been done, avoid duplication, and give due credit to the preceding investigators. The literature search may be properly begun with the "Science Abstracts," Part B, Electrical Engineering. In some cases Part A, Physics, must also be consulted. The corresponding German publication "*Fortschritte der Elektrotechnik*" is also excellent and perhaps more systematic; in addition to abstracts and periodicals it contains new books and patent specifications. The well known "Engineering Index," and the card catalogues arranged by topics and found in the Engineering Societies Library in New York, in Carnegie Library in Pittsburgh and in large college libraries are also great helps. The indexes to the leading electrical magazines and transactions should also be consulted.

4. When planning some research or invention try to think of it in the light of the past and future development of the subject, and not as a detached little investigation of your own. This means that you must connect your work with that of former investigators, and present your results in definite form so that the following investigators can connect them with their work and profit by your labors.

5. There are problems on which no one is working, either because the situation is premature, or because others became discouraged through lack of results. There is an advantage in working on such a problem. Should you succeed, your credit

and recognition will be so much greater. On the other hand, you are much safer working on a problem already staked out by others, where you are merely developing a detail. Some prefer exploring the wilderness, others keep near to beaten paths.

6. Almost any problem mentioned in the following list may be made as short and elementary or as long and thorough as is desired, from a superficial undergraduate thesis finished in a few weeks, to an expert's deep research carried on devotedly through a long series of years. Do not "bite off more than you can chew," but whatever you decide to do, do it well.

7. Do not try to maintain secrecy regarding your work, but try to draw into it and to interest in your problem as many other able persons as you can. Both you and they will be benefited thereby. Consider yourself to be but a thief's apprentice who is learning how to steal nature's secrets, but is not actually doing it yet.

8. Having made a patentable invention or obtained a patent do not try to hold it for an exorbitant price. Dispose of it on the basis of a reasonable sum down and a moderate royalty per year or per piece sold. If you have a real inventor's stuff in you, you will make many more important and lucrative inventions. Dispose of your first effort as soon as possible; it will be an encouragement for your further work.

ELECTRIC GENERATORS AND MOTORS

Output Coefficients. Theoretical justification and limitations of the D^2L formula.
Values of flux density, ampere-conductors per centimeter of periphery, and current density in actual machines.
General study of the best utilization of active iron and copper.
Elements of cost of machinery.

Heating and Ventilation of Machinery. Flow of heat along and across laminations, along copper conductors, across slot insulation, through thick field coils, etc.
Heat transfer between various surfaces and the air, stationary and in motion.
Temperature distribution in a given machine, and bettering its performance by more effective cooling.
Forced ventilation.
Cleaning and cooling of the air.
Rating for intermittent service.

Commutation in Direct-Current Machines. Actual phenomena of commutation with and without interpoles, by means of oscillograph.
Commutation on a device imitating an actual armature coil.
Interpoles, effect of their width and saturation; inductive shunts.

Effect of compensating windings on performance.
Study of brushes.
Proposed formulas and theories of commutation, a critical review of.
Approximate methods of integration of the differential equations of commutation.

Mechanical Construction and Stresses in High-Speed Machinery. Support of armature coils; dovetail stresses; vibration of shaft; stray currents in shafts; fastening of field coils; high-speed commutator; stresses in stationary frame; eccentric rotor.

Armature Reaction and Inductance. Armature reaction in d-c. machines.
Armature reaction in polyphase and in single-phase alternators.
Proposed methods for compounding alternators.
Exact theory of armature reaction and practical approximations.
Leakage inductance of windings, and the separation of slot leakage, end-connection leakage, etc.
Theoretical predetermination of leakage inductance.
Transient condition during short-circuit.
Hunting.

Polyphase Induction Motor. Proposed methods for speed regulation.
Performance characteristics and circle diagram above synchronism.
Predetermination of power factor from design data.
Magnetic leakage and its components.
Exact circle diagrams of performance.
Magnetizing effect of distributed windings.
Experimental separation of losses.
Methods for accurate determination of slip.

Single-Phase Induction Motor. Proposed methods of starting.
Rating of the same frame for one, two, and three-phase windings.
Design of a single-phase induction motor.
Experimental and theoretical investigation of the elliptical revolving field.
Circle diagram of a single-phase induction motor.

Single-Phase and Polyphase Commutator Motors. History of development.
Classification of types.
Means employed for improvement of commutation.
Performance diagrams of the principal types of commutator motors.
Comparison from the point of view of speed-torque characteristics.
Comparison from the point of view of commutation.
Experimental study of a commutator motor.
General principles of design.
Complete design of a single-phase railway motor.
Design and construction of a working model, imitating the electrical relations in a commutator motor.
Phase adjusters for improving power factor.

General Design. Factors to be considered in the design of a new line of machines.
Critical comparison of procedure used by various authors.
M. m. f. required for the active layer.
Design of a line of small machines for manufacture in large quantities.

Layout of a factory for production of a given line of electrical machinery.

Improvements in Methods of Testing. Critical study of methods for measuring temperature, core loss and the separation of hysteresis from eddy current.

Measurement of friction and windage.

Resistance measurements.

Methods of loading a machine by means of circulating power (pumping back methods).

Measurement of speed, slip and acceleration.

Load losses in single-phase alternators.

Special Types of Electrical Machinery. Homopolar generator, reduction of brush friction, increase in speed.

Constant-current machine for operating large arc projectors.

Train-lighting generator driven from car-axle.

Automobile starting motor and lighting generator.

Magnetos for ignition.

Synchronous motor with high starting torque.

Electric variable-speed drive for automobiles.

High-frequency alternator for radio work.

Motor-generator set for intermittent load with energy stored in a flywheel, such as are used in steel mill and mine-hoist work.

Combination of an induction motor and a polyphase commutator motor.

Motor-converter consisting of an induction motor and a d-c. generator with inter-connected windings. Permutator or a converter with stationary field and armature and revolving brushes. Thury high-tension d-c. constant-current machine.

Battery boosters and counter e. m. f. sets.

TRANSFORMERS

Leakage Reactance. Experimental investigation of the influence of arrangement and shape of coils.

Theoretical formulas derived from the equations of electromagnetic field.

Influence of unequal distribution of current in large conductors.

Internal vs. external reactance for safety of large systems during short-circuits.

Economic Relations. The best distribution of losses for a given service.

Amount of copper and iron as a function of relative prices of these materials.

Best values of flux and current density.

Influence of Wave-form. Effect upon the voltage drop, upon the iron loss, and upon the stresses in dielectrics.

Temperature Rise. Theory of conduction of heat; experimental data; influence of various factors; safe temperature rise with various materials; devices for forced cooling.

Artificial load for heat run.

Extrapolation of heating and cooling curves.

Connections. Comparison of delta and Y-connections under normal and abnormal conditions.

Analysis of currents and voltages in T and in V connections.

Doubling the frequency by means of two transformers.

Electrostatic Stresses and potential gradient in and around bushings, terminals, between coils, etc.

Extra stresses due to transient conditions.

See also the section on Dielectrics.

POWER PLANT DESIGN AND ECONOMICS

Standardization of electrical equipment for smaller plants.

Elements of first cost and of operating expenses.

Rational methods of charging for energy.

Forms and blanks for accounting.

Safety appliances, emergency devices, labor-saving apparatus.

Parallel operation of power plants.

Division of load between a steam and a water power plant.

Uses of storage battery.

Automatic substations.

TRANSMISSION LINES AND CABLES

Mechanical stresses in towers and in conductors; influence of temperature.

Skin effect in copper covered and steel wire and in stranded cable.

Interference between power and telephone lines; theory, calculation of induced currents, experimental investigation, methods for reducing interference; the general problem of transposition.

Locating faults with the line energized or dead.

Protection against grounds and short-circuits, sectionalization, relays.

Actual experience with lightning and possible conclusions.

Various types of protection against lightning.

Theory of the ground wire.

Current and voltage relations in lines with distributed properties.

Standing and traveling waves; surges and protection against them.

Experimental mechanical apparatus imitating electric waves.

Transient electric phenomena studied experimentally and theoretically.

Kelvin's law of economy and its various practical applications.

Computation of electrostatic capacity and stresses of cables.

Reduction of capacity in telephone cables.

Propagation of signals in submarine cables.

ELECTRIC TRACTION

General Projects. Design of a high-speed underground road for a large American city.

Design of an elevated road for local and express trains.

Electrification of a large steam railroad center.

Electrification of a mountain division of a steam railroad.

Gasoline-electric and straight gasoline cars for light traffic.

Storage-battery car.

Trackless trolley car.

Competition of the motor bus and of the " jitney " with city, suburban, and interurban railways.

The electric truck.
The electric passenger vehicle.
The dual power car.
Electric traction of boats on a ship canal.
Design and organization of repair shops for a large electric-railway system.

Track, Trolley, Signals. Standardization of the materials, and of the methods of operation and maintenance.
Rail corrugation.
Continuous rail, electric welding, thermit welding.
Bond testers.
Stray currents and prevention of electrolysis.
Overhead construction in various classes of service.
Mechanical stresses in trolley wire, in messenger cables, and in the supporting structures; the problem of support on curves.
The surface-contact system.
Sectionalization of trolley circuits in freight yards, in large passenger terminals, etc.
Automatic switching.
Automatic signals.
The problem of safe and quick dispatching of high-speed roads.

Rolling Stock. Quick and accurate predetermination of time-speed curves.
Design of an apparatus for automatic tracing of time-speed curves.
Resistance to motion of single cars and trains.
Special equipment of an electric car or locomotive for various tests and experiments.
Single-phase locomotive with an electro-dynamic converter or with a mercury-vapor rectifier.
The possibilities and limitations of high-tension direct-current traction.
Recuperation of power on electric roads.
Control of high voltages or of heavy currents in an electric locomotive.
Various types of drive; gears, side-rods, direct drive.
Electrically controlled air brakes for high-speed roads.

ELECTRIC LIGHTING*

Light sources: proposed standards; new types of electric lamps; position and shape of filaments, temperature of operation; color characteristics, and effects; design for special purposes; operating mechanisms.

Lighting accessories; optical properties of diffusing and reflecting media; globes, shades, and reflectors for special purposes; "daylight" glass; means for eliminating glare.

Visual photometry; sensibility of photometers; size of photometric field; errors due to instruments; errors due to operator; effect of color sensibility of observer; recording devices; calibrating devices; integrating photometers; flicker photometers; standardization of absorbing solutions; means for eliminating color differences; standardization of conditions of measurement.

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*Contributed by Professor F. K. Richtmyer.

Physical photometry: the selenium cell; the photoelectric cell; the bolometer; the thermopile; absorbing solutions; photographic methods; other chemical methods; new methods.

Studies in illumination: Survey and criticism of present conditions in various types interiors, in streets, etc.; intensity and type of illumination necessary for various purposes; eye fatigue and visual acuity as dependent on intensity of illumination, color, and system used; design of systems of illumination; illumination calculations.

Terminology of illuminating engineering.

Relation of art, architecture, physiology, and psychology to illuminating engineering.

APPLICATION OF ELECTRIC MOTORS*

Industries. Agriculture, automobile, bakeries, boiler works, bottling works, box factories, breweries, brick factories, broom factories, building construction, candy factories, carpet and rug factories, cement, clothing, corn mills, cotton mills, cotton oil seed mills, creameries, dairies, dye works, flour mills, foundries, freight handling, glass factories, glove factories, hardware manufacture, harness factories, ice machines, irrigation, knitting factories, laundries, lumber mills, machine shops, paper box factories, paper and pulp mills, piano factories, pipe mills, planing mills, porcelain factories, railways, refrigeration, rubber industry, shoe factories, shoe repairing, soap factories, spice factories, steel mills, stone quarries, stove factories, sugar industry, tanneries, textile mills, tile factories, tobacco factories, trunk factories, wagon factories, wall paper factories, woodworking factories, woolen and worsted mills.

Classes of Service. Air compressors, blowers, coal cutters, concrete mixers, conveyors, cranes, crushers, dental appliances, dredges, elevators, exhausters, fans, hoists, ice cream freezers, lime kilns, locks, pumps, printing presses, rock drills, sewing machines, ship propulsion, towing machinery, turn-tables, vacuum cleaners, vehicles, washing machines.

MEASURING INSTRUMENTS AND METHODS

General. Study of characteristics, errors, cost of manufacture, etc. of a given type of meter.

Development of a new type to meet competition in price or to avoid infringing certain patented features.

Design of a complete calibrating equipment for a manufacturing concern, an operating company, a testing laboratory, a college, etc.

Special instruments, such as a double tariff meter, a maximum-demand indicator, a volt-ampere meter, an automatic synchronizer, a phase displacement meter; instruments, for recording rapidly-fluctuating currents and voltages, etc.

Instrument transformers. Design, methods of calibration, errors, exact theory, vector diagrams, etc.

Extra-Accurate measurement of various quantities used in electrical engineering, viz., current, voltage, power, resistance, inductance,

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*Contributed by Mr. D. B. Rushmore.

Vol. 35
1916

capacity, speed, acceleration, slip torque, magnetic properties, dielectric properties.

Analysis of methods, errors, applicability in various cases, new devices and new diagrams of connections.

Magnetic Measurements. Measurement of permeability, core loss and retentivity.

Effect of composition and treatment of steel upon its magnetic properties.

Heusler alloys.

Experimental investigation of distribution of a magnetic field, using an analogous condition of flow of heat or electricity through metal, or flow of water?

Detection of flaws in rails by a magnetic method.

Relays. Overload, underload, and reverse load; over or under-voltage, high and low frequency, low power factor.

Merz-Price and similar selective arrangements.

Time characteristics, instantaneous, definite time, inverse time, etc.

Relays for regulating voltage of generators, batteries, feeders, etc.

Regulation of power factor, frequency, speed, etc. by means of relays.

Relays for submarine telegraphy.

RADIO TRANSMISSION*

Methods for producing damped oscillations for transmission purposes.

Methods for producing damped oscillations of particularly constant amplitude for laboratory measurement purposes.

Methods for producing undamped or continuous oscillations for transmission purposes.

Study of radio detectors.

Study of radio amplifiers.

Study of the "beats" receiver and methods for producing oscillations for the same.

Comparison of "tikker" and "beats" receiver for the reception of undamped waves.

Advantages and disadvantages of using the "beats" receiver for damped waves.

Directive radio communication. Study of the variation of signal intensity with varying wave lengths. Methods of modulating the antenna current for radio-telephony.

Design of a compact portable decremeter.

Study of radio measuring instruments.

Design and construction of portable radio sets.

Design and construction of radio apparatus suitable for instruction and demonstration.

Modern theories of propagation of electromagnetic waves (without mathematics).

Experimental determination of "radiation resistance."

Mathematical theory of radio transmission.

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*Contributed by Mr. C. W. Ballard.

DIELECTRICS

Experimental study of various insulating materials under various conditions of service.
Theory of dielectric stresses in two dimensions by means of conjugate functions.
Experimental investigation of distribution of an electrostatic field using an analogous condition of flow of heat or electricity through metal, or flow of water.
Surface resistivity.
Design of high-tension insulators, bushings, transformer insulation, etc.
Reliability of spark gaps of various shapes.
Measurement of extra-high voltages.
Design and construction of a transformer for testing purposes.
Study of insulating oils; development of a practical and reliable test.
Compressed gas as electric insulation.

MISCELLANEOUS PROBLEMS

Agriculture, electricity in.
Amplifiers for weak currents and voltages.
Arc phenomena.
Automobile starting, lighting, ignition.
Atmospheric electricity, oscillograph study by means of an antenna.
Circuit breakers.
Electromagnets.
Farm lighting and power.
Fixation of atmospheric nitrogen.
Fuses.
Heating and cooking; heat accumulators; high-resistivity alloys; temperature control: insulation.
Magnetic separation of iron ores.
Marine applications of electricity; electric drive of an ocean steamer.
Pictures, transmission of, by electricity.
Precipitation of suspended matter; smoke abatement.
Rectifiers, aluminum, cathode ray, mercury, revolving, vibrating contact.
Safety rules, standardization rules, and standard specifications of various associations in this country and abroad; a critical comparison.
Submarine signaling.
Thermo-electricity, generation directly from fuel.
Telegraphy, rapid, multiplex, submarine with alternating currents.
Telephone apparatus for the deaf.
Telephone transmitters of great power; sensitive telephone receivers and relays, phantom circuits.
Water purification by electricity.
Welding, electric.

APPENDIX

In connection with the suggestion that the A. I. E. E. should encourage systematic research under the auspices of its Educational Committee, the following description of the organization and work of the Research Committee of the A. S. M. E. is given by Mr. R. J. S. Pigott, a member of the committee.

> The object of the Research Committee is to promote the investigation of phenomena, operations, or results of experiments concerning fundamental laws on which engineering practise is based, and to place such data in permanent and basic form. The general committee meets at stated intervals to consider suggested research subjects and to appoint sub-committees to do the actual work of research. Generally, the chairman of the sub-committee is a member of the general committee, but not necessarily so. The present sub-committees are those on fuel oil, materials of electrical engineering, safety valves, worm gears, lubrication, clinkering of coal, steam flow meters, laboratory systems and methods; and a committee on investigation of machine tools is under consideration.
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> The chairman and members of the sub-committee either carry on research in their particular field, themselves, by cooperation with manufacturers, or else have the work done by an interested manufacturer. In general, the expense of the research is borne, therefore, by the interested parties and not by the society.
>
> Up to the present time the committee has not presented any final reports, but the work on worm gearing is well under way, and also that on steam flow meters. As research work is usually lengthy, final reports in less than two or three years are not to be expected. As noted in the definition of the activities of the committee, the work may consist in some cases merely of collation of existing data and putting them in usable form, rather than of original research.

DISCUSSION ON SUGGESTIONS FOR ELECTRICAL RESEARCH IN ENGINEERING COLLEGES" (KARAPETOFF), CLEVELAND, OHIO, JUNE 30, 1916.

J. B. Whitehead: There is truth in what Prof. Karapetoff has to say about the products of research from Germany and England. I do not know that it is quite as definite as he would imply, but I have in mind the character and form of the publication of the results of research as given in the German and English periodicals; and the publications of the German and English engineering societies, I think are superior to those of our own. I would make a plea here for a more careful editing of the publications of our American research. Certainly a comparison, particularly of the German publications, with our own will, I think, indicate that there is truth in what I say, namely, that these publications are better prepared. The precautions that are taken in experimental work are better described, and more effort is made, and I suppose more careful editing accompanies the publication of the results of experiments abroad.

As regards the special fields of investigation in different universities and colleges as related to their particular equipment, I do not believe that is a practical suggestion. I think that research is a question of men and minds, more than it is of equipment and location. I do, however, believe that continuation of a particular subject that has once been started is a most prolific and valuable principle to have in mind. It is one, fortunately, which results naturally in the course of events—when a particular line of research develops and a mature student or a professor is conducting research, it is most natural that he should invoke the assistance of the younger men, and the younger men's interest is at once attracted, and so the work continues naturally. This condition obtains in many places now.

I believe that the suggestion of prizes for investigations is a very good one. We have a number of prizes in this country now for conspicuously valuable results of research, but they are, I think, usually given as rewards for completed efforts, for more mature work. I believe the offering of prizes for work done by young men, perhaps before they leave college, would be a very valuable incentive.

The suggestion of a Research Committee is not a new one. I had in my hand before I left my office, and expected to bring with me, a small pink leaflet that perhaps some of those present will remember. It was headed "Committee on Cooperative Research," and I think the date was 1903 or 1904. That leaflet sets forth a number of subjects from which in the minds of the Committee profitable results might be obtained. I was interested to find that a number of the subjects which were suggested in that comparatively short list are still to be found in Prof. Karapetoff's list.

I do not think that the list of subjects, such as given by Prof. Karapetoff, goes very far in helping the investigator on his way.

Fields for study and for investigation are not difficult to point out. I have found in my relation to this subject that it is far more important, not only to suggest the subject, but to outline the attack. It is almost always indispensable that this should be done. Obviously, an investigation cannot be attacked in any direction without a complete survey of the literature and the work which has already been done. It is not possible, however, to entrust to a young investigator a study of the literature and to leave him to work out the lines of his attack. You can point out the literature to a student and tell him where to go so that he can make a survey of the whole field, but even then he cannot digest it. His judgment is not sufficiently matured to enable him to decide which are the contributions most valuable to the particular line of attack he has in mind. I have found much to my discomfort that it is the duty of one who is attempting to inspire research work to go much further than to simply suggest the subject. It is almost invariably a case of outlining the apparatus and the equipment, and generally also ordering it.

Alan E. Flowers: I think a great many colleges have made use of lists of thesis subjects, such as are submitted here, possibly not so long, possibly more varied in some cases. Such a list has very generally been found to be very useful as a starting point, and nothing that I say later should be construed as opposed to the idea of having such lists, but it is certainly true, as Prof. Whitehead has just said, that the most important thing is, that the list should be supplemented by personal interview and by a considerable amount of suggestion and in some cases of instruction.

I am also very much interested in the idea which is advanced in the paper, of giving prizes for research work. It has always been a matter of great regret to me that the original plan for the Edison Medal was not so arranged that the medal would be made available, in some measure at least, for worthy undergraduate theses. As I remember the conditions, there was a certain age limit, and in addition it was provided that the thesis should be entirely the work of one man. In nine theses out of ten, the thesis is the product of two workers. There are several reasons for this. One of them is the necessity in a great many cases, particularly the case of experimental theses, for two observers, and as it is out of the question for a student to hire his observer, he must have a co-worker. This provision eliminated most of the theses of any value.

I think the conditions for such prizes could readily be changed so as to greatly stimulate experimental research work in the case of the undergraduate, and I rather think that there is some need for such stimulation, because the student who conducts an experimental research thesis is greatly handicapping himself as compared with the student who conducts almost any other type of thesis. He is very sure to put in more time on the work; he is very sure to have more worry; and he is very unsure to get results that will satisfy anybody. Anything within reason that can be done to encourage and help the experimental thesis is, in my opinion, worth while doing.

I am quite sure that, however much I would object to an educational committee or a research committee defining what subjects certain places should take, there is a great good to be obtained by getting major lines started at particular places and endeavoring to make it possible to continue that line of work at that place.

The reason I object to the scheme of fastening research subjects on places, is that I believe the most important thing is to keep the door wide open for a large number of individual suggestions. Whenever we begin to use the fixed method, what might be called the autocratic method, it seems to me we are killing off the most valuable and the most useful of the possibilities, that is, the origination of ideas, the origination of subjects, the carrying on of individual work and the encouragement of originality.

Scholarships would help, to a certain extent and possibly the most useful thing would be something in the nature of industrial scholarships, made available, not for the undergraduate, but for the graduate student. The undergraduate student who shows ability in research and has originality, would be encouraged by the prize and he might then very easily be led on to the postgraduate work of great value.

I think that great good might come to the Institute from a Research Committee. I am a member of the Research Committee of the American Society of Mechanical Engineers, and I have been very greatly impressed by the possibilities of that committee's work.

I feel it would be hardly right, however, to leave this subject without saying one more word about "prizes" I mean by that, compensation. I am afraid that at the present time there has come into existence the idea that in research "virtue is its own reward." So far as I can see, the relations between compensation in research work and compensations for other kinds of work is very much to the detriment of the research worker, whether he be working in pure science or applied science. That seems to me a fundamentally wrong condition, and I think it ought not to pass unnoticed. It is not only a question of the right of the thing, but also a question of the amount of work that might be done. It is a question of the encouragement of additional work. I have long had the feeling that there ought to be some special form of compensation, besides whatever there may be in the way of salary, whatever there may be in the way of reputation, that will come to the worker for each particular thing which he brings out. I see no reason why, a research worker, who reaches results of value, and allows them to be put on the market, should not get royalties, should not have the sort of thing granted an independent invention.

The large companies ought to give serious consideration to granting some special royalty or lump payment for each invention developed by one of their workers.

C. E. Skinner: My attitude toward this subject is probably quite different from that of the man in the university, as my whole experience has been in connection with a large corporation. I have many times been asked by university men to suggest subjects for research work. I find it a very difficult thing to do, because it is hard to outline the surrounding conditions to the man undertaking the research. One does not always know the facilities at his command, and the large corporation is, as we all know, whether you are inside or outside, somewhat jealous of the information leading to new things.

I think that some of the cautions, some of the advice, given by Prof. Karapetoff are very good indeed, and I am not sure that some of his subjects, shown in the list, are not too large. I frequently tell my associates that no matter what a subject is, no matter how small it seems to be, if one goes into it completely—going into literature the first, which should always be done, going into the investigation with a view to finding out about all that can be found out about a particular thing—the subject will grow and the interest will grow.

It very often happens that the by-product of the research is of far greater value than the direct result. A research may be entirely successful when it proves that the object sought cannot be attained. It is very hard for young men, particularly, to get that viewpoint, that the proof that a certain thing cannot be done in the way he had an idea it could be done is of as much value, perhaps, as the doing of the thing he sought. It practically always transpires that in the case of doing research of that kind there are some by-products which are extremely valuable and make very good leads for further research. Having that in mind the suggestion of continuous work on a subject when once undertaken is very good.

I have been very much interested in the last year with the attempts of some of the British people in endeavoring to match up, if possible, with the German research. This war has brought home to the English, as nothing else could possibly do, the desirability of working in advance of anything they have hitherto done. I think that ought to come to us in America in the same way. We have had a stimulus here in the enormous orders for material, and we have had a stimulus in the cutting off of many materials which before the war were available, and research in industrial lines is going along at a very rapid rate. The English people feel that on account of their having a very large number of relatively small corporations, that it may not be possible for any one of these corporations to carry on the work in an entirely satisfactory way. Consequently, they are talking of a co-operative research arrangement which would take in the industrial corporation, the university, and whoever else might be interested. There is a germ of thought there for us, that some sort of co-operation is desirable.

It is not easy for the industrial corporations to line up on this matter of research, on account of the fact that most industrial corporations in this country depend for their business on the protection given by patents. Patent protection, as we all know, is a difficult enough matter as it now stands, without having the added difficulty of the suggestion proposed, that is, the research being made by the corporation, andthen the idea developed, patented by some one outside, with no control by the corporation resulting. If our business is founded on patent protection, then we must have control, and while the work of the university can be of great assistance, it is difficult to tie that up in a satisfactory way with the control that must be had by the industrial corporation.

I have stated on a number of occasions, that it was a shame to have the equipment which is possessed by many of the universities, idle three hundred and sixty out of the three hundred and sixty-five days of the year, when many companies would have been glad, if they could get possession of that equipment, to use it three hundred days in the year and make it efficient. It is too much like the farm machinery which is used, for, let us say, one week of the year, and the rest of the year it stands out in the weather. There is any quantity of such equipment in the technical universities of the country which ought to be efficiently used and used throughout the greater part of the year.

Just what arrangement can be made for accomplishing this desirable result of cooperation between the corporation, which must use the results, and the individual research worker, either undergraduate or post-graduate, I am not sure. I have worked out a few individual cases, but more with a view of training research men than any hope that the work in the school would be very productive, so far as actual researches were concerned. As a training for research men, it has proven very valuable.

F. C. Caldwell: It does seem that some kind of co-operation between the various engineering colleges where thesis work, both undergraduate and graduate, is being done, would be very desirable. We must all feel the lack of effectiveness that we experience in connection with much of this work. Along the line of what Mr. Skinner has said, we have to remember that the primary object of undergraduate research, is not the production of valuable results, but the training of men, who are largely beginners, so far as this kind of work is concerned.

What is needed is some kind of clearing house between the various institutions to help in avoiding unnecessary duplication of work. In some cases, especially with undergraduate work, recognized duplication is a good thing, on account of the checking of the results obtained. This also would be facilitated by such an arrangement.

One other point is perhaps suggested in one of Professor

Karapetoff's items, the desirability of selection of the men who are to do undergraduate research. We try to guide men who seem to have no talent for investigation, and no very great interest in it, into other kinds of thesis work. We give them a design or a compilation, and thus reserve the energy of the instructing force and the equipment for the few men who seem to give promise of really accomplishing something in the way of research and of really gaining something by the training which their work along this line will give them.

E. E. F. Creighton: I think the most valuable suggestions regarding research work were given by our President in his address at the opening of the Convention a few days ago. This whole question, especially the educational side, is of the utmost importance. There is not the slightest possibility at the present time that we can have too much research taught. More theses should be written, beginning with a student's freshman year. Progress is dependent mostly upon research and invention. The idea seems to have gone around that the inventor has an especially fine mind, that he was born clever. I think it is a misconception. There are degrees of ability shown in lawyers, mechanics, doctors, engineers, inventors, and so on. It is not a question of relative ability in these several activities, but training. Research and invention come from the suitable concomitant attitude of mind or view-point. Invention can be taught as readily and as certain of results as any of the professions. A definite course of educational work could be laid out, I believe, which would produce inventors by thousands. Most of the training in life, from infancy, is opposed to the production of inventors. It is too much to discuss at this time but, briefly put, I believe inventors would appear in numbers if everybody would give the mental attention they now apply to "What will people think of me if I do?" to "What will nature do for me if I do?"

To show the results of the attitude of mind I wish to draw a contrast. In a big organization they have their work divided into many different departments. Two of these are Sales Department and Invention or Research Department. The attitude of the mind of a salesman is such that he could not possibly invent. The attitude of mind of the inventor is such that he makes an extremely poor salesman. The salesman must always look to the attractive points, the advantageous points of the things he has to sell. These are known colloquially as the "talking points." He must so impress the purchaser. On the other hand, the research man or inventor must skim over the things that go right and he must worry himself night and day about the little things that go wrong. Start an inventor out in the sales business, and he will tell the prospective customer all the things that are wrong about the apparatus rather then the things that go right.

Before the war started, we had an organization of advanced students in industrial work, and it fell to my lot to take these students, who were all graduates of colleges, for two, three, or six months and use them in the laboratory. I have had many illuminating experiences. I got far enough in this work to be able to tell, with a fair degree of certainty, where a man came from simply by watching how he went at his work. One illustration—three men were independently given a problem, and I was unable to see them again for two days. The first man went to the University library where he combed the shelves for information on the subject. It happened to be an investigation of a new type of protective apparatus. He reported that he was sorry that he was away from the big libraries where he could consult the authorities. (Incidently there were no authorities on this subject.) The second man was of a mathematical turn, and he sat down with a pencil and got his fundamental equation started, and attempted to solve the problem by differential equations. He had landed at the point where he had an expression that he could not solve. The third man did not think about looking up published material, and tried no mathematics, but he went into the shop and commenced to make up a device to try out.

Now, of these three men, the first one was educated in Paris, and like the French, venerated the authorities in science. That was his view-point. The second man was educated in one of our best eastern colleges, where they do a great deal of still thinking and a great deal of mathematical work, and although his tastes, as I found subsequently, were such as to allow him to do experimental work, he had been trained to immobile thinking. The third man was from the good old wooly West where they have not formed the habit of looking up the subject or referring to some authority. It seems to me that "try it" is the fundamental need in all research work.

Some time ago I had the pleasure of giving some young men a chance to train themselves for invention. To help me prove my point,I found that as soon as they got the view-point of the inventor they could invent on short notice. I remember one instance, where two of them made three inventions in ten minutes. All of these inventions did not ripen into patents, but, nevertheless, they caught the view point and invented.

We often hear discouraging remarks made to young investigators stating that they are beginning to investigate before they have had any training. It is a great mistake to assume that one must be familiar with current scientific facts before beginning to investigate independently—very much book knowledge is liable to be an overwhelming handicap and a damper to one's enthusiasm. The kindergarten is the place to begin investigation and invention. The work of Mari Montesorri is one of the best illustrations of this theory. If her methods could be carried along through the grammar schools and the colleges the scientific world would move forward in leaps and bounds.

In the university world I know of one professor who, I think, has the proper view-point for training investigators. Professor

Sanford of Stanford University started his work, and is still carrying it on, in the face of a great deal of opposition. In his course in physics he took away the books from the students and gave them a lot of simple apparatus to work with and set them at it. The criticisms of his methods, especially by the engineering students, were—I can characterize them in one expression—"If I were a Faraday, I could get something out of that course." That is a great mistake. Every investigator must have a start. I have been surprised at the young fellows who have worked with me, who have made an investigation, gathered their data, and then not knowing what to do with it, have gone to some book to find out what it might mean.

As a last proof that my theory is correct, I will cite the case of the Italian janitor in our laboratory, whom I set to work on research work. He has embarrassing moments with his arithmetic and spelling, but nimble fingers and an active mind are gathering in much useful data.

D. D. Ewing: It seems to me the trend of the discussion has been mostly along the line of invention. I think that there is a great deal of research work that can be carried on in a university, that does not have anything to do with invention. Research work on subjects like the one which forms the basis of the paper following this one, "Tractive Resistances to a Motor Delivery Wagon on Different Roads and at Different Speeds," is a fair example of what I have in mind. Traffic studies relating to the transportation of passengers, the delivery of freight, the relation of traffic to schedules and car routing, and great variety of other engineering economic subjects are fruitful lines of research, the work on which can be carried on in universities as well as anywhere else. We should not get it into our heads that the only kind of research work is the research work which leads to invention.

Regarding the alignment of research work in universities and colleges, I think that that depends on whether the research work is being done for the purpose of pure research and the results which come from such research, or whether it is being done for the purpose of training young men.

I object to spoon-feeding the students. Too much alignment and guidance are not good for the student. The primary function of the university, in my opinion, is to train men and not to get definite results in research work. Such results, however, as we do get I think should be recorded where they may be available to all, and that, to me, is the crux of Prof. Karapetoff's paper. I desire to say a word regarding another line of research mentioned in Prof. Karapetoff's paper, namely, that of library researches. Such work, I believe, can be carried on in the university to better advantage than in the factories of manufacturing companies, or by engineers, or by the research men of operating companies, because of the library facilities that are available to university men. I think that one of our great difficulties, at least at Purdue

University, is to get men to do library research. The students all want to do experimental research. Prof. Flowers indicated that he had some difficulty the other way. I feel, however, there is a great field for university research along that line. As has been pointed out in the paper a resume of the various lines of thought and scientific endeavor would be very useful, and this could be carried on by the universities.

Practicing engineers could co-operate in a very helpful manner with the university research men in the suggestion of subjects which are along economic or other lines not leading to invention. I readily appreciate Dr. Skinner's statement regarding the matter of invention. I can see why the manufacturing companies would not care to have such research carried on in the universities, but, on the other hand, all those researches which do not lead to invention could be carried on in co-operation with operating companies, and I think a great deal of value would result from it. Further the research work in this country would be greatly stimulated if we had a little better cooperation between the parties interested in such work.

C. Francis Harding: I wish to bring up one or two points concerning which I am, to some extent, in opposition to the author of the paper, particularly with regard to the question of prizes. I do not believe that a monetary prize or any other prize is going to develop research men or induce them to take up research investigations in the university. I think possibly that some prestige, some honor, which might be conferred on such a man, possibly some recognition by the Institute such as the publishing of the paper, or that which the Engineering Society of Western Pennsylvania offers in connection with its thesis investigations would be far preferable to holding out a prize of $25 or $50, whatever it might be, for the man who would carry on the best research investigation. The latter would take on the form which the university degree assumes for such men who are working to get the sheepskin only, and not for the training which the sheepskin represents.

I do not believe, to take up another question treated in the paper, that it is necessary for the Institute or any other body to suggest subjects. Any live man who is connected with a university, talking half an hour with an engineer of a manufacturing company, or of a public utility corporation, can find readily a large number of subjects which are available and worthy of research investigation, and which his institution is best fitted to undertake. Such may have either a practical bearing, or possibly some value as an invention.

I feel that any action which the Institute may be able to take such as appointing a Research Committee or along any other line which will lead towards further co-operation between the universities and the men of the manufacturing companies and the utilities interested in research, will be to the mutual advantage of the student, the universities and ultimately we hope, to the manufacturing companies and the Institute as well.

N. S. Diamant: We may disagree with Prof. Karapetoff as to specific suggestions made in the paper, but I think we shall all agree that it is high time that universities raise their standards of *scholarship* and *research* and do their share along with the industrial corporations. It may not be exaggerating the importance of the subject to say that it will prove a national calamity if they do not.

Research is not something as mechanical as a glance at the paper may suggest, and in regard to it we may well refer to President Carty's address and abide by his advice and some of his suggestions.

The average standard of scholarship and research at present is very low—considering the universities all over the country—and the author seems well justified in using the expression "superficial undergraduate thesis" with emphasis on superficial.

In regard to the quantity and quality of work that has been done so far in the United States and in Europe—as I would add Switzerland, France, Belgium, etc., to the countries mentioned by the author—I am afraid both Mr. Whitehead and Prof. Karapetoff are right in their comparison—the European work in general seems to be more thorough, and to be published in a more *scholarly form*, not only from a *technical* point of view but *literary* as well.

J. J. Carty: The distinction which I made in my paper between pure scientific research and industrial research is a distinction which I think should be borne in mind all of the time in considering questions such as these. I have frequently heard during the discussion here, the term "research," employed as though it meant but one thing. It really means two things. There is pure scientific research and industrial scientific research, and the necessity for this distinction is well illustrated when we come to discuss the ethics of publication as applied to the two cases.

Pure scientific research is conducted for the purpose of extending the boundaries of knowledge and publication is one of the goals. It is ethical to publish these results; it would be unethical not to do so.

When it comes to industrial research the ethics of the case are different. The industrial scientist is employed by a manufacturer or other client to make a scientific investigation at his expense and for his benefit. It would be unethical for the industrial scientific research worker to publish the results of his investigation until his client gives him permission to do so; that is, until the client has determined to his own satisfaction that he will not be injured by the publication.

There is no obligation whatever upon the manufacturer to give out to his competitors scientific information obtained at his expense and for his benefit. The manufacturer embodies the results of his scientific investigations in practical form and benefits the public through the improved product which he provides. Almost invariably, however, the results of industrial scientific investigation are published in due course, as a rule this publication being in the form of an issued patent, which is the method adopted by our form of government to take the place of trade secrets. I am told, however, that there is such a thing as property in trade secrets and if you will read the remarkable paper by Mr. Frederick P. Fish on "The Ethics of Trade Secrets," you will find there a great deal of interesting and curious information upon this subject.

The question as to whether our universities or technical schools should undertake industrial scientific research is a large one which is now being carefully studied by many who are interested in the subject. It is certain that if the technical schools are to carry industrial research work to the point of taking problems from the manufacturer and solving them for pay, the manufacturer will insist upon a contract with the university whereby the publication of the results will be forbidden until such time as he is protected by issued patents, or for other reasons concludes that his interests will not suffer by the publication.

I do not wish to imply that there is no place for industrial research in the universities or technical schools. This question is now being seriously studied. I hope it will be found that there will be a great deal that they can do. I hope to see spring up near the universities large industrial research laboratories and if it is found that they can be successfully associated with the universities, all the better.

In any event, as soon as our manufacturers have awakened to the importance of industrial scientific research, I believe industrial laboratories will spring up everywhere and that the universities and technical schools will find it difficult to graduate in sufficient numbers, men trained in the rigorous methods of the pure scientist to carry on the work of industrial research.

D. H. Braymer: I was interested in the remark of one of the speakers, comparing American journals with foreign journals. I think I have an explanation. It is hardest to obtain the results of research work from professors and universities themselves. It is next easiest to get it from the manufacturing companies, and it is easiest of all to get it from the research departments of the operating companies. Operating engineers interested in new developments are always glad to tell what they have done, why they have done it, and what they are going to do. I can see no reason why there should not be the same attitude toward a publication on the part of the universities and the manufacturers.

A. A. Nims: We are thinking today in terms of the nation rather than in terms of the individual. Five of the national engineering societies are just completing an important step in the preparedness program upon which the country has entered. It is, therefore, appropriate and significant that we have brought to our attention, as convincingly as Professor Karapetoff has done, another service wherein the same societies, with others, can render effective aid in furthering that larger preparedness for national co-operation of which military readiness should be an incidental phase.

Scientific research has not been regarded with that degree of respect by those who might devote their talents to it, nor has such reliance been placed upon it by those who might use its results, as has been accorded it elsewhere. The writer has a distinct recollection of the distaste and dissatisfaction with which senior thesis was regarded at the engineering college from which he graduated. The fellows looked upon thesis work as "not practical," *i. e.* unrelated to the work they expected to take up after graduation, or else themselves unfitted to accomplish results commensurate with the effort expended. Hence the majority of them considered there were other more profitable uses for their time, and since senior thesis has been made elective few take it.

The business firms that are able to maintain adequate equipments for effective research are vastly outnumbered by those who are unable, and who acquire their new technical information by accident or by appealing to some outside agency for the solution of special pressing problems. Occasional, unrelated research, inspired by sporadic inquiries, is more expensive, less effective and commands less confidence than well-organized, well-directed, continued effort. The economics of a high load-factor applies to a plant for scientific research in the same manner, though not to the same degree, that it does to a plant for producing electric energy.

With research encouraged and coordinated throughout the country, students would gradually take a different attitude toward their first encounter with such work. Inquiries on various subjects would be referred to the best authority, securing the most reliable information in the shortest time.

It is quite possible that one of the greater and more lasting benefits of the present commercial activity under limited supplies of materials may be found to lie in the fact that it opened our eyes to the incompleteness of our scientific and technical knowledge and compelled us to take systematic means to extend it. It is, therefore, greatly to be hoped that Professor Karapetoff's suggestions may lead to constructive action along the lines pointed out.

Alexander Gray: The technical press is not able to obtain original articles from the universities because the universities are not turning out good stuff. Most of the research that is started is never completed because there is a lack of men of research ability and because the men available are not properly guided. The large corporations take the best of the men and some of those that are left become teachers.

The original work done in most of our schools does not begin to compare with that done by the manufacturing companies and it is not because of lack of equipment. What we need rather is men like Kelvin of Glasgow, Thomson of Cambridge and Arnold of Karlsruhe to guide our graduate schools, but such men do not seem to develop in our universities.

One of the speakers considered it inadvisable to offer prizes for research. I have seen how two prizes offered to engineers for public speaking have set a whole senior class to work by giving direction to its thought.

Prof. Karapetoff is right when he insists on the schools limiting themselves to one or two subjects rather than spreading their energy over a large number of disconnected subjects. Only by years of work in a given field can results be obtained that are of great value, and only in this way can the work be carried on from year to year with instructors always coming and going.

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TRACTIVE RESISTANCES TO A MOTOR DELIVERY WAGON ON DIFFERENT ROADS AND AT DIFFERENT SPEEDS

BY A. E. KENNELLY AND O. R. SCHURIG

ABSTRACT OF PAPER

In this paper is given a complete report on an investigation of tractive resistances of urban roads to a motor delivery wagon equipped with solid rubber tires. The "tractive resistance" as used in this paper, includes still-air resistance, but does not include wind resistance and the resistances internal to the truck. The test truck is fully described with its driving mechanism and the storage battery which supplied the motive power. The investigation involved test runs over definite lengths of road, at measured truck speeds, to determine the gross battery output during these runs; and laboratory tests to determine the overall efficiency of the truck between battery terminals and rear-wheel treads at speeds and loads corresponding to the road tests. The results included in the paper are (1) overall efficiency of truck mechanism and (2) tractive resistances of a number of typical urban roads. The components of tractive resistance for a typical road are also given.

THE INVESTIGATION herein described was carried on in the Research Division of the Electrical Engineering Department, at the Massachusetts Institute of Technology, during the year 1915, under a fund contributed for researches on motor trucks.

Object of the Research. The object of this research was to determine the resistance, including air resistance, offered to an electric truck, by level urban roads of different surface varieties, at standard truck speeds not exceeding 25 km. (15.5 miles) per hour. For this purpose, the output of the storage battery on a test truck was measured, for both directions of travel, over standard road beds, at different controller speeds. From this output were deducted all the corresponding electrical and mechanical losses in the truck mechanism, as determined by laboratory tests. The remainder of the output was consequently attributed to (1) road- (2) air- and (3) wind-resistance. The wind resistance was eliminated by averaging the results for both directions of running, leaving as the final result the sum of the road and air resistances.

By "road resistance" is meant the horizontal force required to pull the truck, assumed as internally frictionless, over the horizontal road, in the absence of air. By "air resistance" is meant the horizontal force on the truck required to overcome the resistance of the air, assumed as quiescent in the absence of the truck. By "wind resistance" is meant the horizontal force on the truck necessary to overcome the resistance of the wind velocity, or that velocity of the air with respect to the ground which exists in the absence of the truck.

THE TEST TRUCK

Through the courtesy of the manufacturer, a 1000-lb. (450-kg.) worm-drive, single-reduction electric truck, or delivery wagon, was placed at the disposal of the Research Division for the purposes of the test. A picture of this truck is given in Fig. 1. Its specifications are as follow:

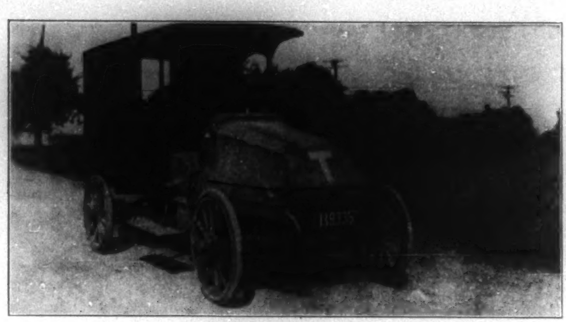
Load capacity 1000 lb. (450 kg.) equipped with one d-c. series motor.

Overall length of frame	4280 mm.	168½ in.
Width of frame	890 mm.	35 in.
Wheel base (*i. e.* distance between centers of front and rear wheels, when front and rear axles are parallel)	2730 mm.	107⅝ in.
Wheel gage	1470 mm.	58 in.

The total weight of the truck, including motor, battery and body, but without load or passengers, was 4200 lb. (1910 kg.). Each of the four wheels was equipped with one solid-rubber demountable tire (manufactured for this type of delivery wagon) rated at 36 in. by 2½ in. (91.5 cm. by 6.35 cm.), and actually measuring about 35 in. (89 cm.) tread diameter, and 2½ in. (6.35 cm.) width of base. The brakes were of the internal expanding type on each rear wheel.

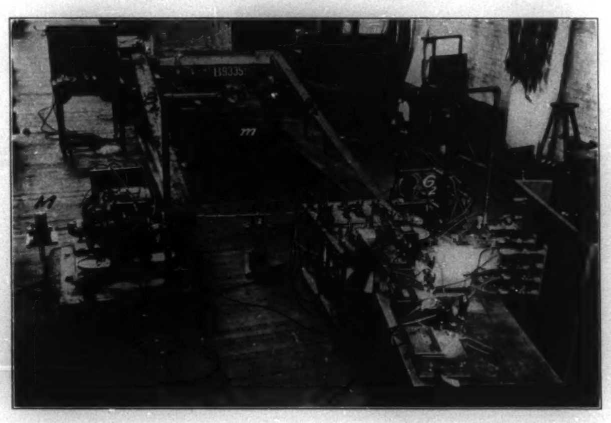
A cross section of the rear wheel, showing bearings and tire, is seen in Fig. 2. Fig. 3 is a drawing of side and front elevations of the truck. This type of electric truck is commonly used for city and suburban parcel-delivery service.

The transmission system was of the shaft type, the speed reduction between motor and rear wheels being accomplished by a single worm with worm wheel, *i. e.*, the motor shaft is extended, through two universal joints, *U* (Fig. 3), which allow for spring compression due to load and impact, to the worm *W* (Fig. 4). Through *W*, the rotation is transmitted to the worm-



[KENNELLY AND SCHURIG]

FIG. 1—VIEW OF TEST TRUCK


119335
777
M
G2

[KENNELLY AND SCHURIG]

FIG. 8—VIEW OF TEST ARRANGEMENT FOR TRUCK EFFICIENCY

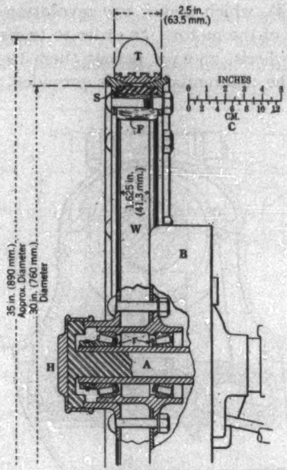

2.5 in.
(63.5 mm.)
T
S
F
INCHES
0 1 2 3 4 5
0 2 4 6 8 10 12
CM.
C
1.625 in.
(41.3 mm.)
W
B
35 in. (890 mm.)
Approx. Diameter
30 in. (760 mm.)
Diameter
r
A
H

FIG. 2—CROSS-SECTION OF REAR-WHEEL BEARING WITH WHEEL AND TIRE

T demountable solid-rubber motor tire, rated at 36 in. by 2½ in. (915 mm. by 63.5 mm.)
S steel band
F bent felloe
W wheel with 12 spokes
B brake drum, containing internal-expanding brake (details not shown).
r tapered roller bearings
H hub cap
A rear-wheel axle
C approximate scale.

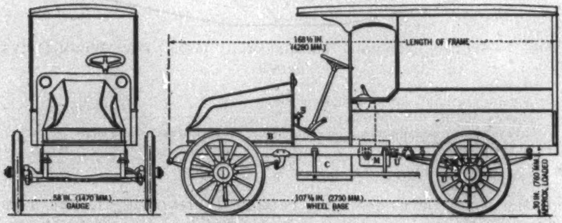

168½ IN.
(4280 MM.)
LENGTH OF FRAME
S
B
C
M
U
U
s
58 IN. (1470 MM.)
GAUGE
107½ IN. (2730 MM.)
WHEEL BASE
30 IN. (760 MM.)
APPROX. LOADED

FIG. 3—SIDE AND FRONT ELEVATIONS OF TEST VEHICLE

B Battery compartment containing 45 cells
C Battery compartment containing 15 cells.
M Truck motor
UU Universal joints
S Driving shaft connecting motor and worm gear
s Speedometer

wheel *R*, (Fig. 4), which makes one revolution for every nine of the worm, or of the motor. In order to transmit the motive power to both wheels, and yet permit them to revolve at different speeds, the differential gear is provided, which consists of the small bevel gears *gg*, capable of revolving about axes fixed to the worm wheel *R*; the small gears *gg* mesh with the two bevel gears *bb*, of which one is fixed to the right-hand section, and the other to the left-hand section of the rear axle. The corresponding shaft bearings of the roller-bearing type are *rr*.

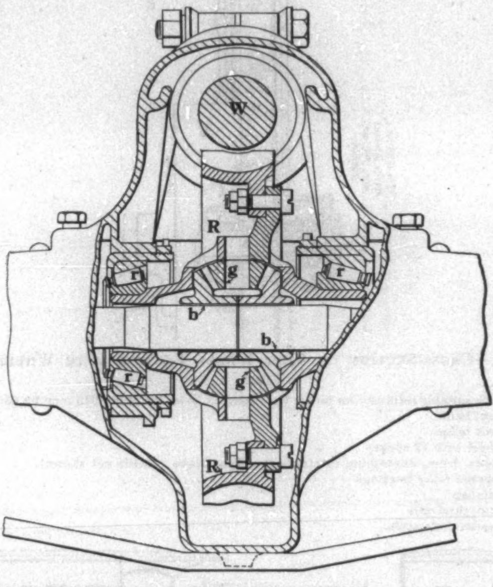


FIG. 4—SECTION THROUGH DIFFERENTIAL GEAR FOR WORM-DRIVE TRUCK

W worm
R worm wheel; ratio of worm to worm-wheel = 9:1
gg gears attached to worm-wheel *R*
bb bevel gears meshing with *gg* and connected to sections of rear-wheel shaft
rr tapered roller bearings

Driving Motor and Controller. The electric motor *M*, Fig. 3, has the following specification: No. 282,666, E20, W 2, 32 amperes, 60 volt, 1200 rev. per min. The manufacturer's test data for this type of motor are given in Fig. 5.

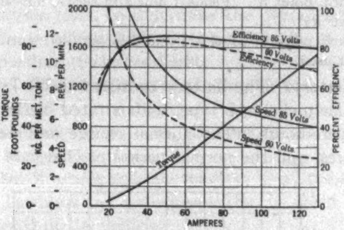


FIG. 5—MANUFACTURERS' CHARACTERISTIC CURVES FOR AUTOMOBILE MOTOR

60 volts—32 amperes—1200 rev. per min.—the two series field windings are connected in parallel with each other

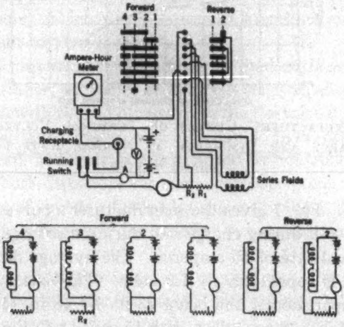

Forward
4 3 2 1
Reverse
1 2
Ampere-Hour Meter
Charging Receptacle
Running Switch
A
V
Series Fields
R_2 R_1
Forward
4
3
2
1
Reverse
1
2
R_2

FIG. 6—DEVELOPMENT OF CONTROLLER AND DIAGRAM OF CIRCUIT CONNECTIONS

The controller is of the following description: Type S-35, Form A. It is of the drum type, having four forward and two reverse speeds.

The connection diagram of the controller and motor is given in Fig. 6.

The operation of the controller is as follows:

*Forward, point 1. Fields 1 and 2 in series, all starting resistance in series with armature and fields.

*Forward, point 2. Fields 1 and 2 in series, all starting resistance short circuited.

Forward, point 3. Fields 1 and 2 in series, but shunted by resistance R_2

Forward, point 4. Fields 1 and 2 in parallel, starting resistance not used.

Storage Battery. The battery consisted of 60 Type A-6 cells of the regular nickel-iron type, with a rated discharge capacity of 225 ampere-hours. The normal charge and discharge rate is 45 amperes, and the normal period of charge is seven hours at this rate. Fig. 7 gives the manufacturer's curves of terminal voltage per cell during charge and during discharge, in each case at the normal rate of 45 amperes. The average discharge voltage per cell is approximately 1.2 volts. The battery was placed in two compartments, one being 23 in. by 18 in. (58 cm. by 46 cm.) and 15 in. (38 cm.) deep with 15 cells at *C*, Fig. 3; another being 40 in. by 31 in. (102 cm. by 79 cm.) and 15 in. (38 cm.) deep, with 45 cells at *B*, (Fig. 3.)

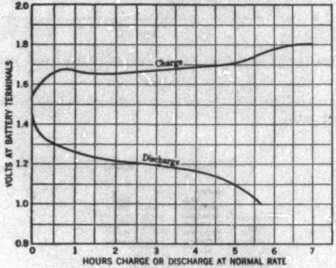


FIG. 7—MANUFACTURES' CURVES OF TERMINAL VOLTAGE PER CELL DURING CHARGE AND DISCHARGE AT NORMAL RATE FOR ALKALINE STORAGE BATTERY

The entire battery with solution, trays and connections, weighs approximately 1200 lb. (550 kg.)

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*Reverse, point 1, same as forward point 1, except that direction of current through series fields is reversed.

Reverse, point 2, same as forward point 2, except that direction of current through series fields is reversed.

Experimental Procedure

The tests made were of two kinds; namely,

(1) Road tests, over selected measured lengths of road, at different measured truck speeds, to determine the gross battery output.

(2) Laboratory tests, to determine the overall efficiency between battery terminals and rear-wheel treads, at speeds and loads corresponding to the road tests.

Road Tests. The resistance (excluding air-resistance) offered by a level roadbed to a moving truck, depends upon

(1) The surface quality; *i. e.*, the smoothness, hardness and resilience of the road surface.

(2) The size of wheel and tire quality; *i. e.*, the dimensions, smoothness, hardness and resilience of the tire tread.

(3) The speed of the vehicle.

(4) The load or weight of the vehicle.

(5) The construction of the vehicle, *i. e.*, whether with or without springs.

In these tests variations in (2) and (5) were eliminated, by using the same vehicle and the same type and size of wheel and tire throughout, which fairly represent standard average conditions for half-ton truck service.

In order to investigate the effects of road surface quality on tractive resistance, stretches of nearly level typical urban roads were selected, with the aid of records in the Boston City Engineers office. Runs were made with the truck over each selected stretch of road, at nearly constant speed by controller, and successively in both directions for each controller point, thus covering the range of speeds afforded by the controller. The effect of load in the vehicle, upon the tractive resistance, was also tried in a few cases.

The technique of the tests was as follows: Previous to the first test of the day, the car storage battery was fully charged. The car crew consisted of one driver and two observers. The driver confined his attention to steering the car, while running at constant controller position. If the driver had to change the controller position, or apply the brakes, during the run, the run was repeated.

The first observer was stationed on the front seat, beside the driver, and noted the stop-watch times of start and finish, as well as the readings of the speedometers during the run.

The second observer was stationed in the body of the truck, and continuously took readings of voltage and current at battery terminals, by calibrated measuring instruments; these instruments being supported on cushions to minimize their vibration. The positions of these instruments in the battery circuit are indicated in Fig. 6 at *A* and *V*.

The start and finish for each stretch of road were marked off by chalk, or other clearly visible lines, drawn across the roadway. The car was always set in motion at a suitable distance behind the starting line, so as to reach approximately steady speed when this line was crossed. A stop-watch was started by the first observer at this moment. It was stopped by the same observer at the moment when the front wheels of the car crossed the finish line. The reading of the stop-watch was thus the time of the run.

The length of the run between start and finish lines was determined by means of a tape line. The runs varied in length from 400 ft. (120 m.) to 2600 ft. (790 m.)

Wherever the grades of the test stretches were not obtained from the city maps, they were measured directly, on special days, by the car observers, with surveyors' level and rod, in the regular way.

For each controller speed, the car was run three times in each direction, over the test section, in immediate succession. By this method of running in alternate directions over the same section, the effect of wind on car resistance was approximately eliminated, on the assumption that if a wind was blowing, it was uniform in velocity, and tended to exert a uniform pressure on the car, whether the latter was running with it or against it. No heavy windstorms occurred during the period selected for the tests. The arithmetical mean of the road resistances, as measured at nearly constant speeds in opposite directions, was assumed to eliminate the effect of wind velocity.

A further correction, namely that due to the change of kinetic energy inparted to the vehicle, between start and finish, became necessary, because the speed was not absolutely constant during the run; *i. e.*, a slight retardation or acceleration took place over the test stretch, in spite of the fact that the controller was not changed, that roads of uniform grade were selected, and also that the truck was started as far in advance of the mark as was practicable. The energy imparted to a truck which is accelerating includes not only that necessary to overcome its internal and external resistances, but also that definite amount of energy which is required to produce the acceleration. The latter portion of energy is known to be equal to

$$\frac{1}{2}\,\frac{W}{g}(v_2^2-v_1^2) \qquad \text{kg.-m.}$$

where W is the mass accelerated (kg.), v_2 and v_1 being the velocities in m. per sec. at end and at beginning of the run, respectively; g is the mean constant of acceleration due to gravity, *i.e.*, 9.81 m. per sec. This energy was subtracted from the total energy imparted to the truck. The importance of this correction and the method of its application in a typical case may be seen from Table III.

Table I contains a sample set of observations made in a particular run in alternate directions over a test section.

Laboratory Tests. In order to determine the truck-mechanism overall efficiency, from storage-battery terminals to tire treads, as already referred to, the car was taken into the Lowell laboratory, the rear wheels raised from the ground, and belted each to a load-generator. The motor was then operated through the controller, at a number of speeds, the power being delivered to the load-generators and measured over a considerable range of speeds and outputs. Fig. 8 gives a photographic view of the test arrangement. The car B-9335 is shown, with its rear axle supported on I-beams. The rear wheels are belted to two similar 5 h.p. d-c. generators G_1G_2, loaded by banks of adjustable *Ia-Ia* resistors R. Fig. 9 gives a diagram of the electrical test connections.

The speed of the rear wheels, in these laboratory tests, was measured by means of the magneto m (Fig. 8), belted to one of the wheel brake drums. It was also checked by means of the magneto M coupled to one of the load generators G_1. In order to ensure equality in speeds of the two truck wheels, under test conditions, so that the load might be equally divided between them, and that the conditions might correspond to those when the car runs on a straight path, a slip counter c was inserted between the two generator shafts, so as to indicate, by the flashing of a light, if their speeds materially differed.

The load generators were separately excited. Their output was measured by d-c. voltmeter V, and ammeters A_1A_2, Fig. 9, in their respective circuits. Separate tests were made on the load generators G_1 G_2, to determine their mechanical and electrical armature losses, under different load conditions. These

TABLE I.
SAMPLE SET OF OBSERVATIONS FOR TYPICAL TEST RUN

Run No. 19. *Length* 900 ft. (274 m.) *Gross Weight* 4710 lb. (2140 kg.) *Date* June 15, 1915.
Location = Beacon St., Brookline, Mass.
Start = (east) mark in curb at crossing of Kilsyth St., Elevation: 0
Finish = (west) " " " " Strathmore Road, " +4.3 ft. (1.31 m.)
Description = tar macadam, in good condition, surface wet.
Weather = cloudy, misty rain; wind east; temp. 60 deg. fahr. (15.5 deg. cent.)

Controller Point 1.

	1st Run						2nd Run						3rd Run					
Time	63.6 sec.			51.0 sec.			63.0 sec.			51.4 sec.			62.4 sec.			53.6 sec.		
Direction	West			East			West			East			West			East		
	Battery output		†km. per hr.	Battery output		†km. per hr.	Battery output		†km. per hr.	Battery output		†km. per hr.	Battery output		†km. per hr.	Battery output		†km. per hr.
	volts	amp.		volts	amp.		volts	amp.		volts	amp.		volts	amp.		volts	amp.	
	80	29.5	16.3	81	22.5	19.1	79	28.5	16.3	80	23.0	18.3	81	27.5	18.1	80.5	24.8	18.0
	80	30.1	15.6	81	21.5	21.1	79	29.0	15.9	80	22.5	20.1	81	28.5	16.6	80.5	24.0	18.7
	79.5	30.1	15.3	81	22.5	19.7	79	28.5	15.9	80	22.5	19.7	80	29.5	15.1	80.5	23.8	18.2
	79.5	29.5	15.6	81	23.0	19.1	79	29.5	15.9	80	22.5	19.1	80	29.5	16.1	80	24.0	19.1
	79.5	28.5	15.3	81	23.0	21.1	79.5	29.5	15.6	80	22.5	18.6	79.5	30.1	15.3	80	23.8	18.7
	79.5	29.5	15.3	81.5	22.5	18.7	79.5	29.0	15.3	81	23.8	19.7	79.5	30.8	15.3	80	23.8	18.0
	79	30.1	15.7	....	....	19.1	79.5	28.5	15.3	81	22.5	19.7	79.5	29.5	15.3	80.5	23.0	19.1
	....	....	15.3	....	....	19.1	79.5	29.0	15.6	81	22.0	....	79.5	29.5	15.3	80.5	23.0	....
	....	....	15.3	....	....	19.1	79.5	29.0	15.6	81	22.0	....	....	....	....	....	....	....
	....	....	14.7	....	....	....	78.5	29.5	15.6	81	22.0	....	....	....	....	....	....	....
	....	....	....	....	....	....	78.5	30.8	15.3	....	....	....	....	....	....	....	....	....
Averages	2360 watts		15.4	1830 watts		19.6	2310 watts		15.7	1810 watts		19.3	2350 watts		15.9	1910 watts		18.6
			15.5*			19.4*			15.7*			19.2*			15.8*			18.4*

†Speedometer readings.

*Speed (km. per hr.) obtained from stop watch readings and distance measurement. East West
Average battery output (watts)..............................2340 1850
Average speed by stop watch (km./hr.)......................15.7 19.0

NOTE: Two independent speedometers were employed and read in each test; in the above table one set of speed values has been omitted. Calibration corrections have been applied to instrument readings.

losses added to the outputs, gave the total generator inputs supplied through the driving belts.

The losses in the two driving belts B_1 B_2, Fig. 8, were approximately determined by taking two successive light load tests, first with the regular heavy leather belts shown in Fig. 8, and next with special light cotton belts of negligible power loss, but of very limited transmitting capacity. The difference between the inputs, in these two tests, measured the power consumed in the leather belts; because the other losses in the two tests were the same.

The friction losses in the front wheels (about 70 watts total), were also measured by belting them to the rear wheels through light belts in special tests. No allowance was made for any possible increase in wheel-bearing friction under increased gravitational pressures; but since all the wheels had roller axle bearings, such extra friction losses were probably very small.

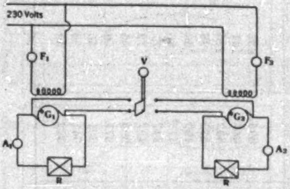

Fig. 9—Diagram of Connections for Determination of Test Truck Over-All Efficiency by Means of Load Generators G_1 and G_2

*Each generator was belted to one of the rear truck-wheels

The sum of the load-generator outputs, the armature losses, and belt losses, was taken as the car output at rear-wheel treads, at various measured inputs.

A detailed quantitative analysis of these various losses appears in the next section.

Results of Tests

Although the primary object of this research has been a determination of tractive resistances to an electric truck, under the conditions previously defined; yet, incidentally the tests have furnished results of practical value of the overall efficiency from battery terminals to wheel treads of this type of electric car, under normal operating conditions.

Overall Efficiency of Driving Mechanism. A summary of typical data obtained in one of the laboratory tests is given in Table II. The first column gives the output in watts at the battery terminals, determined from the simultaneous readings of a calibrated voltmeter and ammeter, *V*, *A*, Fig. 6. Column II gives peripheral wheel speeds in km. per hr. and in miles

TABLE II.

DATA AND RESULTS FOR OVERALL EFFICIENCY OF TEST TRUCK

CONTROLLER ON POINT 4 FORWARD; BATTERY FULLY CHARGED.

I.	II.		III.	IV.	V.	VI.	VII.	VIII.	IX.
Battery output	Peripheral rear wheel speed		Sum of generator outputs	Losses for generators			Sum of gen. outputs and losses	Equivalent truck output on road	Overall efficiency per cent
				Armature copper	Stray power	Belt losses			
watts	km./hr.	miles/hr.	watts	watts	watts	watts	watts	watts	
1860	31.6	19.7	0	0	895	237	1132	1066	57.3
2390	25.7	16.0	872	4	645	161	1682	1616	67.6
2770	23.1	14.4	1289	11	632	130	2062	1996	72.0
3350	20.0	12.4	2001	36	529	98	2664	2598	78.5
3570	19.2	11.9	2230	50	499	90	2869	2803	78.5
3790	18.3	11.4	2420	65	471	86	3042	2976	78.5
3980	17.6	10.9	2560	80	447	77	3164	3098	77.8
4130	17.0	10.6	2656	96	427	72	3251	3185	77.2
4470	16.1	10.0	2920	132	399	65	3516	3450	77.1
4720	15.6	9.7	3090	167	377	59	3693	3627	76.8
4940	15.0	9.3	3270	204	361	56	3891	3825	77.5
5075	14.5	9.0	3317	236	341	53	3947	3881	76.5
5290	14.3	8.9	3274	262	322	50	3908	3842	72.7

per hr., derived from the voltage readings of magnetos M, m, Fig. 8. Column III gives the total generator output as determined by simultaneous readings of calibrated instruments V, A_1 and A_2, Fig. 9. Columns IV, V and VI itemize the following losses: (IV) armature copper losses (watts) in generators G_1 G_2, as obtained by resistance measurements of armatures, and from the observed armature currents (ammeters A_1 A_2, Fig. 9.); (V) stray-power losses (watts) in generators G_1 G_2, as determined from special stray-power tests, already referred to; (VI) belt losses; *i.e.*, frictions in both driving belts B_1 and B_2, as determined by special belt-loss tests, already mentioned. Column VII gives the sum of the losses in columns III, IV, V and VI. Column VIII gives the equivalent output of truck on road, as obtained by subtracting from the watts tabulated in column VII, 66 watts for average front-wheel friction, the latter as determined by the special front-wheel friction-loss test already mentioned. The last column gives the overall efficiency of the car for road runs, *i. e.*, the ratio of columns VIII and I.

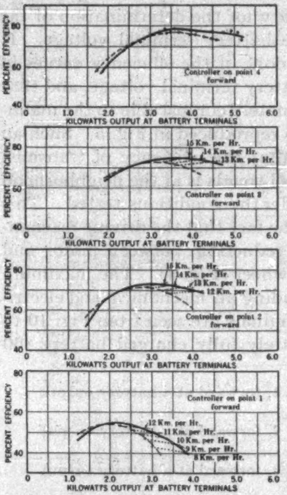

FIG. 10—CURVES OF OVERALL EFFICIENCY OF TEST TRUCK

With battery fully charged (full lines)—and with battery partially discharged (dash lines)—Dotted lines are drawn at constant rear-wheel peripheral speeds, as indicated—60 alkaline cells, type A6, were used.

Efficiency tests as elaborated in Table II were made at each controller position for forward speeds. In view of the relatively large voltage variation (see Fig. 7) of the truck battery, between full charge and partial or complete discharge, and at different current outputs, it was found necessary to perform efficiency-test runs; (1) at a fully charged battery and (2) at a partially discharged battery, (1) corresponding to high impressed voltage and (2) to a slightly lower impressed voltage. The results of the efficiency tests are shown in Fig. 10. It is seen that the condition of the battery has a considerable effect upon the results. Fig. 10 shows, besides efficiency curves at fully charged battery (full lines), and at partly discharged battery (dash lines), a number of constant speed lines (dotted). For example, the overall road efficiency of the truck at 3500 watts battery output, controller on point 2, and at a truck speed of 13 km. per hr. (8.1 miles per hr.) is 71 per cent from Fig. 10. It was for convenience in the handling of the data that the truck speed was chosen as the third factor necessary for the determination of the truck efficiency, rather than the battery terminal voltage. It should also be pointed out that none of the efficiency curves in Fig. 10 are drawn at constant battery terminal voltage, and that they are, therefore, only approximately comparable to the manufacturers' motor efficiency curves reproduced in Fig. 5. Such an approximate comparison shows that the efficiency of transmission between motor and rear-wheel treads is in the neighborhood of 90 per cent for this truck under the conditions tested. This high value may be attributed to the fact that the driving mechanism involves but a single speed reduction, between motor and rear axle, by a worm and worm wheel (Fig. 4). The maximum values of over-all efficiency, including all mechanical and electrical losses beyond the battery terminals are seen from Fig. 10 to be as follow, when an approximately fully charged battery (60 cells, type A 6)is employed.

55 per cent, controller on point 1, forward at a battery output of 2000 watts.

73 per cent, controller on point 2, forward at a battery output of 3000 watts.

75 per cent, controller on point 3, forward at a battery output of 3500 watts.

78 per cent, controller on point 4, forward at a battery output of 3700 watts.

Tractive Resistance. The complete data and results for tractive resistance are shown, for a typical test run, in Table III. In columns I and II are tabulated the controller position and the direction of run, respectively, as previously defined. The speed (average of stopwatch readings divided into measured length of run for three consecutive tests) is given in column III. Column IV contains the average battery output in watts, already referred to (See Table I). Column V contains the number of meters of rise of elevation between start and finish. The average time of run (see Table I) is shown in column VI. The truck over-all efficiency, as taken from the efficiency curves (Fig. 10), is tabulated in column VII. Columns VIII, IX and X contain the follow-

TABLE III.

TEST DATA AND RESULTS FOR RUN NO. 19

Gross weight = 2140 kg. (4710 lb.)
Length of run = 274 m. (900 ft.)
Description of Road = Tar macadam.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	XIII.	XIV.
							Power losses (watts)						
Cont. pos.	Dir. of run	Speed $\frac{\text{km.}}{\text{hr.}}$	Batt. output watts	Incr. of elev. m.	Time of run sec.	Overall eff. of truck per cent	In truck	Against gravity	Due to change of kin. energy	Total	Tract. power watts	Tract. resist. $\frac{\text{kg.}}{\text{met.ton.}}$	Equiv. per cent grade
1	W	15.7	2340	+ 1.31	63.0	54.5	1063	436	−76	1423	917	10.0	1.0
2	W	18.3	2370	+ 1.31	53.9	70.0	712	510	− 9	1213	1157	10.8	1.08
3	W	19.6	2600	+ 1.31	50.4	71.0	755	546	20	1321	1279	11.2	1.12
4	W	21.8	2970	+ 1.31	45.2	75.0	743	608	80	1431	1539	12.1	1.21
1	E	19.0	1850	− 1.31	52.0	54.0	850	−529	48	369	1481	13.4	1.34
2	E	20.9	1920	− 1.31	47.4	65.5	662	−580	117	199	1721	14.2	1.42
3	E	22.4	2050	− 1.31	44.2	66.0	696	−621	118	193	1857	14.3	1.43
4	E	24.5	2500	− 1.31	40.2	69.5	763	−683	271	351	2149	15.0	1.50

TABLE IV.

TEST DATA AND RESULTS FOR LOSS OF POWER DUE TO CHANGE OF KINETIC ENERGY OF TEST TRUCK FOR RUN 19

Controller point	1		2		3		4	
Direction of run	West	East	West	East	West	East	West	East
v_2 average speed at finish $\frac{\text{km.}}{\text{hr.}}$	15.1	19.3	18.25	21.8	19.8	23.0	22.6	26.2
v_1 average speed at start $\frac{\text{km.}}{\text{hr.}}$	16.9	18.5	18.4	20.2	19.5	21.7	21.6	23.5
$v_2^2 - v_1^2$	− 58	30	− 6	67	12	58	44	134
Average time of run, sec.	63.0	52.0	53.9	47.4	50.4	44.2	45.2	40.2
Average power lost in accelerating truck, watts	− 76	48	− 9	117	20	118	80	271

ing power losses in watts: VIII in truck, as obtained from IV and VII; IX against gravity; X due to change of kinetic energy of truck between start and finish (see table IV), all of which losses are supplied by the storage battery. In column XI are tabulated the sum of the entries of columns VIII, IX and X. The difference between IV and XI gives the total tractive power, as recorded in XII. Column XIII contains the tractive resistance in kg. per metric ton as derived from XII. The last column contains the equivalent percentage of grade, since 10 kg. per metric ton is just equivalent to 1 per cent grade.

The test data and results for loss of power, due to change of kinetic energy of the truck, for a typical road test are tabulated in Table IV. The results are negative for runs in which the velocity decreased. It is seen from the magnitude of these results, that they are by no means negligible. In practically all the road tests, this item was found to be of importance.

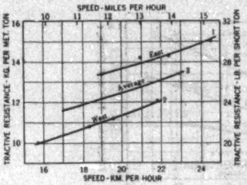

FIG. 11—CURVES OF LEVEL-ROAD TRACTIVE RESISTANCE FOR RUN 19

Pavement: tar macadam in good condition wet—wind east—curves 1 and 2 include the effects of the wind resistance —in curve 3 these effects are approximately eliminated, but not the still-air resistance.

In Fig. 11 are plotted the results for a typical test, in accordance with Table III. The ordinates of curve 3 represent the horizontal force per metric ton, and per short ton, which is required to overcome the road resistance, and still-air resistance, at constant speed on level road, with no wind blowing. Curves similar to those of Fig. 11 were plotted for each road test. A summary of the tests is represented by Figs. 12 to 18 inclusive.

Asphalt Roads, (Fig. 12.) The curves plotted in Fig. 12 apply to both sheet asphalt (*a*) and to bitulithic pavements (*b*), both defined as follow: (*a*) asphalt, consisting of (1) a foundation of hydraulic cement or concrete, (2) a binder course of broken stone and asphaltic cement (dissolved asphalt), (3) a surface layer of asphaltic cement mixed with sand; (*b*) bitulithic pavement, which may be classified as a type of asphalt-macadam pavement, built on a concrete, stone-block or macadam foundation, consisting of a mixture of broken stone, sand and asphaltic cement, proportioned and mixed before being laid. This mixture, after having been laid hot, and rolled, is covered with a coat of hot asphaltic cement and fine stone chips.

The tests showed that there was no appreciable difference between the tractive resistances of sheet asphalt and bitulithic pavements as above defined when in good condition; so that both of these pavements are represented on one and the same diagram Fig. 12. The asphalt pavement, when in good condition, offers a low resistance to vehicular traffic, on account of its smoothness and hardness. Curve (1) is seen to be almost flat, and if the still-air resistance is eliminated by an approximate formula*, a straight horizontal line, (see curve 5), results for the road resistance alone. Curves 2 and 3 are steepened by the addition of impact and vibration losses. These extra losses are due to the impacts which the truck receives as it encounters local lumps and hollows in the worn pavement. The dash-line curve was obtained when the total moving mass was increased 12 per cent, and is seen to be almost identical with curve 1.

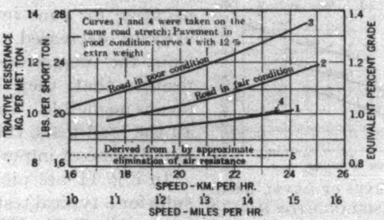

FIG. 12—TRACTIVE RESISTANCE FOR ASPHALT ROADS

Sheet asphalt and bitulithic.

Wood-Block Roads, (Fig. 13). The full-line curve of Fig. 13 applies to wood-block paving, which consists of rectangular creosoted hard-pine blocks, approximately 4 in. (10 cm.) deep, 3.5 in. (9 cm.) wide and 8 in. (20 cm.) long, placed, with the fiber vertical, and the long dimension crosswise to the street, upon a foundation of concrete with a thin layer of sand interposed between concrete and wood blocks. The curve is nearly horizontal because of the smoothness of the pavement.

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*$P = 0.0025 \dfrac{A . V^2}{W}$ lb. per short ton

air resistance, in which formula A is the cross-section of the car in sq. ft., V the speed of the car in miles per hr., and W the total mass in motion (in short tons); see American Handbook for Electrical Engineers, 1914, Wiley, New York, p. 1166. In metric units, the above equation takes the form

$P = 0.0047 \dfrac{av^2}{w}$ kg. per metric ton

if a is expressed in sq. m., v in km. per hr. and w in metric tons. The area offered to the air by the test truck was approximately 14 sq. ft. (1.3 sq. m.) and the moving mass was 2.36 short tons (2.14 met. tons), except when otherwise noted.

Brick-Block Roads, (Fig. 13). The brick-block roads upon which tests were made, consisted of rectangular vitrified paving brick, approximately 4 in. (10 cm.) deep, 3.5 in. (9 cm.) wide, and 8.5 in. (21.5 cm.) long, laid with the length perpendicular to the curb, upon a foundation of concrete and a cushion layer of sand. The results for brick roads show nearly as low a resistance as those for the wood block, but the curve for the former is steeper, particularly for the case of a worn surface, again probably because of the impact and vibration losses on the rougher pavement.

Vol. 35
1916

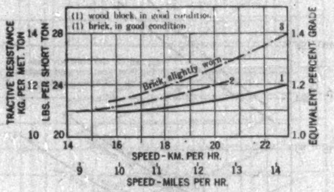

FIG. 13—TRACTIVE RESISTANCE FOR WOOD-BLOCK AND BRICK-BLOCK ROADS

Granite-Block Roads, (Fig. 14). The foundation for these roads is either a bed of sand, or a layer of concrete, with a sand cushion to separate the blocks from the concrete. Average dimensions for the rectangular blocks are about 4 in. (10 cm.) wide, 11 in. (28 cm.) long and 8 in. (20 cm. deep). The joints are filled either with small pebbles and sand, or with hydraulic-cement grout. The former filler is subject to being partially washed out by precipitation, and removed by the street sweeper, and thus allows the edges of the blocks to be exposed to wear, which renders the pavement far less smooth than one with cement-filled joints. The full-line curves 1 and 2 in Fig. 14, which apply to granite-block roads with cement-filled joints, show a greater upward slope than those for the smoother brick-block, wood-block, and asphalt roads, already mentioned; while the granite-block pavements constructed with the less durable filler are seen to offer a still more rapidly increasing resistance at increasing velocities, because of the greater losses of kinetic energy due to road impact.

Macadam Roads, (Fig. 15 and 16). This type of road has a pavement consisting of several layers of broken stone, (trap rock, granite, lime stone, slate, etc.) ranging in size from about 3 in. (7.6 cm.) to about 0.5 in. (1.3 cm.) in largest dimension. The fragments of stone are held together by a binding material of which there are two general types: (1) clay, loam, sand, or finest screenings (stone dust from stone crusher), distributed over each layer of broken stone, water being sprinkled over the surface; and (2) tar, either mixed with the broken stone before it is laid, or distributed over the broken stone, after the latter has been spread and rolled; type (1) is known as a water-bound macadam, and type (2) as tar-macadam.

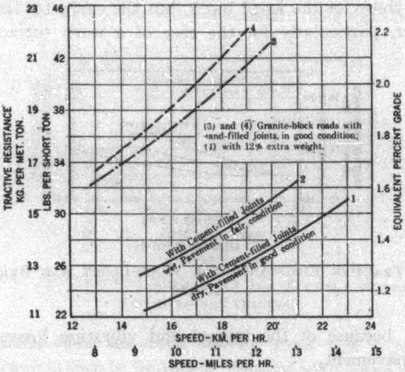

FIG. 14—TRACTIVE RESISTANCE FOR GRANITE-BLOCK ROADS

Fig. 15 shows the results obtained for water-bound macadam roads, the dot-dash curves apply to the oiled pavements, full-line curves are for unoiled roads. A dusty road (curve 2), is seen to have a greater resistance than a similar one with a hard surface without dust (curve 1); while a badly worn road with holes (curve 3), shows a far higher resistance than 1 and 2, and a much more rapid rise with increasing speed, due to impact losses. Curve 4 for an oiled macadam road, though in fair condition, shows a higher resistance than a similar road unoiled. Heavy oiling increases the resistance without increasing the slope of the curve, as indicated by curve 5; this effect is probably caused by the softening of the surface and the resultant loss of power due to the depression of the surface material by the wheel tires. The combined effects of wear and oil are seen in curve 6. Curve 7, if compared with curve 5, (the two curves applying to the same road, but to different days and different total weights of moving vehicle), shows a slight increase of resistance due probably to both decreased road resilience and increased weight.

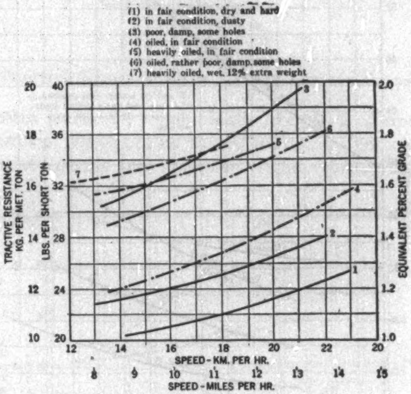

FIG. 15—TRACTIVE RESISTANCE FOR MACADAM ROADS

The results for tar-macadam roads, (Fig. 16) are similar to those for water-bonded macadam; *i.e.*, the effects of surface deterioration are definitely seen by comparison of curves 1, 2, 3 and 4. Curve 5 is of interest in again demonstrating that the resistance of a soft surface of low resilience is greater than that of a similar but hard road by an approximately constant amount, (see curves 5 and 1). The dash-line, curve 6, (12 per cent extra weight), is seen to follow very closely curve 2, (the two curves include data obtained on the same road under similar conditions, but with different total weights.)

Cinder and Gravel Roads (Fig. 17.) Curve 1 in Fig. 17 applies to a road with a gravel surface, in fair condition, but slightly dusty. A cinder road with a dry and hard surface in fair condition, is seen to have a slightly lower resistance, probably because of its greater resilience.

Summary for All Classes of Urban Roads Tested. Typical results for all classes of urban roads tested are summarized graphically in Fig. 18, and numerically in Table V. It appears from these summaries, and from the foregoing discussions, that there are three principal elements which determine the tractive-resistance-speed curve for unit weight of a given vehicle, within the range of conditions covered by this test:

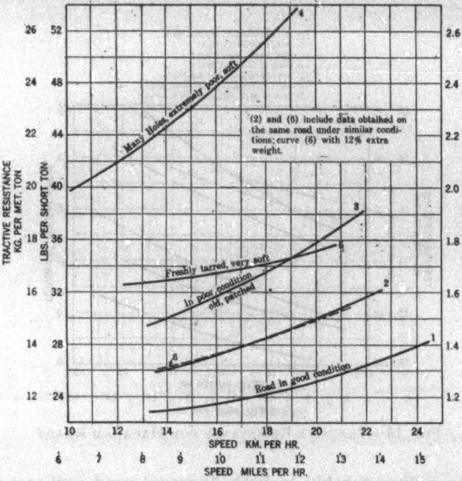

FIG. 16—TRACTIVE RESISTANCE FOR TAR-MACADAM ROADS

(1) A constant resistance, see curve 1, Fig. 19*, the magnitude *A* of which depends on the lack of resilience of the road surface and wheel tire material, *i.e.*, on the energy losses due to displacement of tire material and road-surface material. This constant element *A* would be encountered upon a smooth level road

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*The quantitative data of Fig. 19 refer to the asphalt roads of Fig. 12.

of the particular type considered, in the absence of impact, air, and wind-resistances.

(2) An increasing resistance with increasing speed, due to impact losses (curve 2), which results from lack of smoothness of road surface; losses of this nature are usually known to vary approximately as the second power of the velocity at impact; and

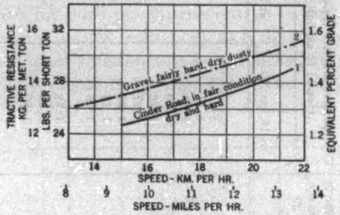

FIG. 17—TRACTIVE RESISTANCE FOR GRAVEL AND FOR CINDER ROADS

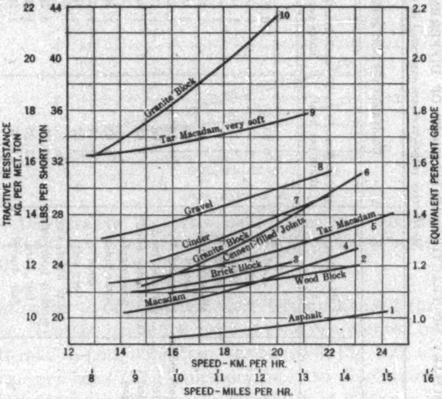

FIG. 18—SUMMARY OF TRACTIVE RESISTANCE TESTS

(3) An increasing resistance with increased speed, due to air pressure against the front of the vehicle, curve 3, which resistance is known to depend, roughly, on the second power of the speed (see above under "Asphalt Roads"). The sum of the three

TABLE V.

SUMMARY OF TRACTIVE RESISTANCES OF DIFFERENT URBAN ROADS AT DIFFERENT SPEEDS

All tractive resistances are expressed in equivalent per cent grade.

Road		Equivalent per cent grade		Per cent increase in tractive resistance from 16 to 20 km. per hr.	Comparative tractive resistance factors referred to asphalt roads	
Type	Condition	at 16 km./hr. (10 miles per hour)	at 20 km./hr. (12.4 miles per hour)		at 16 km./hr.	at 20 km./hr.
Asphalt	good	0.93	0.97	4	1.0	1.0
Asphalt	poor	1.03	1.16	11	1.11	1.20
Wood block	good	1.10	1.15	5	1.18	1.18
Brick block	good	1.12	1.21	8	1.20	1.25
Brick block	slightly worn	1.14	1.27	11	1.23	1.31
Granite block	good	1.83	2.16	18	1.97	2.23
Granite block with cement joints	good	1.16	1.37	18	1.25	1.41
Macadam, water bonded	dry and hard	1.06	1.17	10	1.14	1.20
Macadam, water bonded	fair, heavily oiled	1.63	1.76	8	1.75	1.82
Macadam, water bonded	poor, damp some holes	1.65	1.89	15	1.78	1.95
Tar macadam	good	1.17	1.27	9	1.26	1.31
Tar macadam	very soft	1.67	1.76	5	1.80	1.81
Tar macadam	many holes, extremely poor, soft	2.38	2.75	16	2.55	2.85
Cinder	fair, hard	1.25	1.39	11	1.35	1.43
Gravel	fair, dusty	1.37	1.50	9	1.47	1.55

curves for items 1, 2, and 3, for the case of asphalt roads in Fig. 12, results in curve 4. The constant resistance (1) may be briefly called the *displacement resistance*, item 2 the *impact resistance*, and item 3 the *air resistance*. The displacement resistance is low for hard pavements (curve 1, Fig. 12) and high for soft pavements (of low resilience), as is illustrated by curve 5, Fig. 16; The impact resistance is very marked in granite-block roads, as already mentioned, (Fig. 14). The air resistance, at any definite velocity, is the same for all curves; because the air-resisting parts of the truck were left unchanged throughout the tests. For the particular type of road represented by Fig. 19 (asphalt road in poor condition, see curve 3, Fig. 12), at a speed of 20 km. per hour (12.4 miles per hr.) the displacement resistance is 0.84 per cent, the air resistance is 0.11 per cent, the impact resistance 0.20 per cent and the total 1.15 per cent equivalent grade.

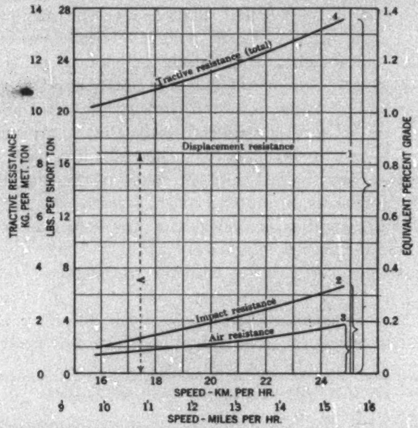

FIG. 19—APPROXIMATE ANALYSIS OF TYPICAL TRACTIVE RESISTANCE INTO ITS ELEMENTS, FOR ASPHALT ROAD IN POOR CONDITION (CURVE 3, FIG. 12)

The displacement resistance of a road manifestly varies, not only with the type and surface quality of the road, but also with the type, dimensions and quality of the tires on the wheels of the vehicle. In the tests here reported, the same tires were used throughout, and they remained in substantially the same condition.

The impact resistance of a road manifestly depends not only on the type and surface quality of the road, and the sizes of its irregularities; but also on the type, dimensions and quality of the wheel tires, the weight of the truck, and the quality of its springs.

The air resistance per unit weight of truck manifestly depends upon the weight, dimensions and shape of the vehicle, as well as on the speed of the vehicle relatively to the surrounding air.

The wind resistance per unit weight of truck manifestly depends upon the weight, dimensions and shape of the vehicle, as well as on the direction and velocity of the wind and the velocity of the vehicle. It is assumed that at low wind and vehicle-speeds, like those here considered, only that component of the wind which is in the direction of the vehicle's path needs to be taken into account, and that the mean of the wind resistances in opposite directions, along the road, is zero.

The following studies are suggested for future experimenters along the line of this investigation:

(1) Researches on vehicle tractive resistances on country roads.

(2) Tractive resistances to vehicles with different wheel tires.

(3) Tractive resistances of urban roads at low speeds from 0 to 10 miles per hour (16 km. per hr.)

(4) Tractive resistances at speeds higher than 15 miles per hour, (24 km. per hr.)

(5) Tractive resistances for heavy-duty trucks.

In conclusion, the authors wish to express their indebtedness to Mr. Thomas A. Edison and the Gould Storage Battery Co., who contributed the funds for carrying out the work; to the General Vehicle Co. for the loan of the truck used in the tests; and to the Edison Electric Illuminating Co. of Boston for their helpful assistance in several stages of this research. Further acknowledgment is due to Messrs. A. C. Brown (S. B., M. I. T. 1914) and F. B. Barns, (S. B., M. I. T. 1915), who took most of the observations during road and laboratory tests, and to Messrs. D. J. McGrath (S.B., M. I. T. 1912) and L. H. Webber (S. B., M. I. T. 1914) who rendered assistance in the preparation of the results.

SUMMARY OF CONCLUSIONS

The following conclusions are indicated from the preceding results: as confined to urban roads, with a solid rubber-tired motor truck between the speed limits of from 13 to 25 kilometers per hour, (8 to 15.5 miles per hour.)

(1) The over-all efficiency of the test-truck mechanism, as described in this report, between battery terminals and rear-wheel treads, reached a maximum value of about 78 per cent, under the most favorable conditions.

(2) The mechanical efficiency of transmission from motor shaft to rear-wheel treads, for the truck tested, shaft-driven through a single-reduction worm gear, was found as high as 90 per cent.

(3) Tractive resistances are most conveniently expressed as an equivalent percentage grade; *i.e.*, a level road of definite tractive resistance may be regarded as a road of zero tractive resistance, but rising uniformly x units in 100 units of road length, or having an equivalent grade of x per cent.

(4) Under the conditions of these tests, the tractive resistance on level roads, in the absence of wind, is composed of (a) displacement resistance, (b) impact resistance, and (c) air resistance.

(5) The displacement resistance varied from 0.85 per cent equivalent grade, for a hard smooth asphalt or bituminous concrete to 1.6 per cent for a very soft tar-macadam road, and was practically constant, for all speeds considered, on any given road.

(6) The impact resistance increases with the velocity, with the total weight of vehicle, and with increasing road-surface roughness. In these tests, the impact resistance of good asphalt or bitulithic or other smooth pavement, was practically negligible, and reached its highest values on granite-block roads with sand-filled joints, and on badly worn macadam pavements. The rate of increase of impact resistance with speed was most marked on the roughest roads.

(7) At the vehicle speed of 20 km. (12.4 miles) per hour, the air resistance for the vehicle tested, assumed to be dependent only on the speed, was roughly 0.11 per cent equivalent grade; *i. e.*, from 4 per cent of the highest, to 12.5 per cent of the lowest, total tractive resistance.

(8) The following urban pavements are enumerated in the order of their desirability for vehicle operation from the point

of view of tractive resistance at 20 km. (12.4 miles) per hr., as found in this investigation. (1) asphalt, (2) wood block, (3) hard smooth macadam, (4) brick block, (5) granite block with cement-filled joints, (6) cinder, (7) gravel, (8) granite block with sand-filled joints.

(9) The equivalent grade at 20 km. (12.4 miles) per hr. of a badly worn city macadam road, was found to be nearly three times as great as that of the best asphalt road tested. This means, at this speed, a consumption of energy at wheel treads, of nearly three times as much on level poor macadam roads as on good level asphalt roads.

(10) Increasing the gross weight of the vehicle by 12 per cent, through load, was found to have no effect on tractive resistance within the observed speed limits for smooth roads in good condition; but on rough roads, a distinct increase in tractive resistance with this extra weight was observed.

(11) The presence of a layer of dust, say one cm. thick, on a fair macadam road, was found to increase the equivalent grade of tractive resistance, at all tested speeds, by about 0.15 per cent.

(12) A freshly tarred and therefore very soft tar-macadam road was found to have an increased tractive resistance equivalent, at substantially all tested speeds, of about 0.5 per cent. The tires in this case sank about 0.8 inch (2 cm.) into the road bed, the gross car weight being 2140 kg. (4710 lb.)

(13) The total range of tractive resistance equivalent grade covered in the tests, was from 0.93 per cent on the best asphalt road, at lowest speed, to 2.7 per cent on the worst macadam road, at nearly the highest speed.

BIBLIOGRAPHY

1. A. Morin; "Expériences sur le tirage des voitures et sur les effects destructeurs qu'elles exercent sur les routes, executées en 1837 et 1838 par ordre du Ministre de la Guerre et en 1839 et 1841 par ordre du Ministre des Traveaux Publics"; Paris; 1842[1].

2. Minutes of proceedings of the Institution of Civil Engineers, Vol. LX, p. 302, London, 1880.[2]

3. Studebaker Bros. Mfg. Co.; Pamphlet containing results on effect

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[1] These experiments cover tractive resistances, principally at low speeds of about 3 miles per hr. (4.8 km. per hr.), for gun carriages, freight cars, artillery wagons, freight wagons, stage coaches, carriages, and wagons, (the latter three with springs), on miscellaneous surfaces.

[2] An abstract is given of Mr. M. Bixio's results on tractive resistances to a French four-wheeled cab, weighing 658 kg. (1447 lb.), on stone-block, macadam, and asphalt pavements.

of width of tire upon tractive power for several road surfaces; South Bend, Ind.; 1892.

4. Missouri Agricultural Experimental Station, Bulletin No. 39; Columbia, Mo.; 1897[3].

5. W. Worby Beaumont; "Motor Vehicles and Motors"; pp. 49-59, J. B. Lippincott Company, Philadelphia, 1900.

6. Missouri Agricultural Experiment Station, Bulletin No. 52; Columbia, Mo.; 1902[4].

7. H. E. Wimperis; "Measurements of Road Resistance of Automobiles," *Engineering News*, Aug. 8, 1910, Vol. 64, p. 128.

8. A. Churchward, "The Standardization of the Electric Vehicle"; *The Central Station*: 1912; Vol. 2, p. 254, and Vol. 12, p. 166.

9. E. B. McCormick, "Some Recent Tests to Determine Effects of Grade and Surface of Roads on Tractive Force"; *Engineering and Contracting*, Nov. 6, 1912, p. 515.

10. I. O. Baker, "A Treatise on Roads and Pavements," Wiley, New York, 1913, pp. 21-31.

11. F. E. Whitney, "Electric Vehicle Tires," Electric Vehicle Association of America, Oct. 27, 1913.

12. N. A. Hall and J. M. Hargrave, "Energy Consumption of an Electric Truck on Different Street Surfaces," *Electrical World*, Vol. 61, No. 20, p. 1040, May 17, 1913; Abstract of Mass. Inst. Tech. Thesis, June, 1912.

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[3] Experiments on the effect of tire width on road resistances for various surfaces are reported in this paper.

[4] In this report are given the results obtained by Mr. T. I. Mairs for rolling resistances of wagon wheels of different sizes on various surfaces.

DISCUSSION ON "TRACTIVE RESISTANCES TO A MOTOR DELIVERY WAGON ON DIFFERENT ROADS AND AT DIFFERENT SPEEDS", (KENNELLY-SCHURIG), CLEVELAND, OHIO, JUNE 30, 1916.

A. A. Nims: (communicated after adjournment): There is one factor of tractive resistance which has not been separated and listed in this paper. Its value may be of small significance and perhaps may not affect the accuracy of the results to any great extent, but its existence should be recognized at least, if for no other present reason than technical accuracy.

The authors of the paper define "road resistance" as "the horizontal force required to pull the truck over the horizontal road" and "air resistance" as "the horizontal force on the truck required to overcome the resistance of the air". Eliminating "wind resistance," the power delivered to the driving wheel treads at constant speed on a level road is considered equal to the sum of the power consumed by road and air resistances. Yet, in calibrating the truck, belt losses on the wheel treads are found to be an appreciable item, especially at the lighter loads.

The driving wheels of any self-propelled vehicle do double duty—they carry a large share of the load and also deliver to the road, by a friction transmission, the power for propelling the vehicle. It would therefore seem logical that, in evaluating "the horizontal force required to pull the truck" the losses of the friction transmission, consisting of driving wheels and road, be considered in addition to those transmission losses that occur entirely within the vehicle mechanism. A simple means of covering all these losses is to make the term "vehicle efficiency" include all losses from the battery terminals to the ground instead of to the wheel treads only. When "vehicle efficiency" has this meaning, it may be used to determine a value of vehicle output which, at constant speed on a level road, is equal to the power required to tow the vehicle under the same conditions.

O. R. Schurig: In the discussion communicated by Mr. Nims, the "vehicle efficiency", (*i.e.*, the efficiency from battery terminals to the ground) is mentioned as being technically more accurate than the "overall efficiency of driving mechanism", the latter meaning the efficiency between battery terminals and wheel treads, the difference between the two efficiencies being that in the first, the losses in the tire treads are considered as part of the *vehicle losses*; while in the second, they are considered as part of the power delivered by the *vehicle*. In order to group the tire-tread losses among the vehicle losses, it would obviously be necessary to separate the former from the losses occurring in the road surface proper. Since an accurate practical method for the separation of these two mutually dependent losses is not known to the authors, the "vehicle efficiency" as defined by Mr. Nims seems to be purely theoretical. If the latter efficiency were practically obtainable, it would seem to be less useful than the overall efficiency employed by the authors, because it would be dependent not only on the truck speed and battery output, but also on the nature of the road surface.

The "overall efficiency of driving mechanism" as defined and determined in the paper, (1) is believed to be technically accurate, because it takes account of all components of the power originating at the battery terminals; (2) it is readily obtainable experimentally by the procedure outlined in the paper; and (3) it is the term employed in the determinaton of all those portions of the battery output, which are dependent upon the nature of the road surface, *i.e.*, the joint tire-tread and road-surface losses. These joint losses serve as a basis for the calculation of the horizontal force required to move, at constant speed, a truck having ordinary tire losses, but being otherwise frictionless.

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APPLICATION OF A POLAR FORM OF COMPLEX QUANTITIES TO THE CALCULATION OF ALTERNATING-CURRENT PHENOMENA

BY N. S. DIAMANT

ABSTRACT OF PAPER

In the *calculation* of alternating-current phenomena by means of complex quantities, as a rule, the rectangular components of the vector are used, and the rectangular form involving the operator $j = \sqrt{-1}$ is more common than the polar or exponential forms which involve the operators $(\cos\theta + j\sin\theta)$ or $\epsilon^{j\theta}$; although it is recognized that the latter are very convenient in certain cases.

A simple method for dealing directly with the vectors themselves is described in the paper and it consists in introducing the operator j^n, where n, contrary to ordinary usage, may be any positive or negative fraction. Just as j or j^1 rotates the quantity before which it is placed through 1×90 degrees, so j^n rotates the number into which it is multiplied through $n \times 90$ degrees.

The operator j^n follows the rules of ordinary algebra and according to these the different algebraic operations of multiplication etc., are developed in section II. In section III a few illustrative problems are given; these are followed by a critical résumé in section IV. At the end, for convenience of reference a summary of formulas is given, and a very short bibliography is included.

I—INTRODUCTION

ACCORDING to the usual method of dealing analytically with alternating-current problems a stationary vector[1] representing the harmonic quantity under consideration, is expressed algebraically by a complex number of the following forms:

(*a*) The rectangular form, (see Fig. 1).

$$\underset{\cdot}{E} = e + je' \qquad (1)$$

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[1] As to the classification of vectors into stationary, rotative, non-rotative, etc. an interesting paper by A. E. Kennelly, TRANS. A. I. E. E. June 1910, may be consulted. It should be noted, in this connection, that in electrical engineering we deal with two-dimensional *vector representation of harmonic quantities* rather than the two- or three-dimensional, non-localized true vectors of vector analysis or quaternions.

where e and e' are the rectangular coordinates of the point representing the complex number.

(*b*) The polar form, (see Fig. 1).

$$\underset{\cdot}{E} = E\ (\cos\theta + j\sin\theta) \qquad \textbf{(2)}$$

where $E = \sqrt{e^2 + e'^2}$, and $\theta = \tan^{-1}\left(\frac{e'}{e}\right)$, are the polar coordinates of the same point representing the same complex number. Equation (**2**) can also be written in the exponential form by means of the identity,

$$(\cos\theta + j\sin\theta) \equiv e^{j\theta}$$

Thus

$$\underset{\cdot}{E} = E e^{j\theta} \qquad \textbf{(3)}$$

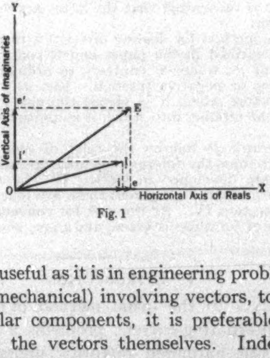

Fig. 1

Convenient and useful as it is in engineering problems (whether electrical, civil or mechanical) involving vectors, to resolve these into two rectangular components, it is preferable at times to deal directly with the vectors themselves. Indeed, it is not uncommon in the derivation of general expressions for regulation, etc., to use vectors rather than their components; for instance, the (primary) impressed voltage of a transformer may be written as

$$\underset{\cdot}{E}_1 = \underset{\cdot}{E}_{i1}(1 + \underset{\cdot}{Z}_1\ \underset{\cdot}{Y}_0 + \underset{\cdot}{Z}_1\ \underset{\cdot}{Y}/a^2), \text{ instead of,} \qquad \textbf{(4)}$$

$$= e_{i1}\left[1 + r_1\left(g_0 + \frac{g}{a^2}\right) + x_1\left(b_0 + \frac{b}{a^2}\right) + jx_1\left(g_0 + \frac{g}{a^2}\right) - jr_1\left(b_0 + \frac{b}{a^2}\right)\right] \qquad \textbf{(5)}$$

Equation (**4**) not only looks simpler than (**5**) but it is a much better *mathematical shorthand*, so to speak, since it allows at a glance to see into the physical meaning of the expression; this is very important and valuable in engineering, both from a practical and educational point of view. Translating (**4**) into words it will be seen that it states in a simple and direct manner that the voltage impressed upon a transformer = (the primary induced voltage) + (the exciting current, $E_{i1}\, Y_0$, times the primary impedance Z_1) + (the load current [reduced to primary] times the same impedance Z_1); where the plus sign signifies vector addition.

In *actual calculations*, however, so far as the writer is aware, in standard a-c. engineering works or technical papers, use is made of expression (**5**) rather than such an equation as

$$\underset{\cdot}{E}_1 = e_{i1}\left[1 + Z_1 e^{j\alpha}\left(Y_0 e^{-j\beta} + \frac{Y}{a^2}\, e^{-j\gamma}\right)\right]$$

$$= e_{i1}\left[1 + Z_0\, Y_0\, e^{j(\alpha-\beta)} + Z_1 \frac{Y}{a^2}\, e^{j(\alpha-\gamma)}\right] \qquad (\mathbf{6})$$

The object of the paper is to discuss briefly the use of a simple polar form of complex quantities and indicate some of its advantages when used either by itself or in combination with the usual present day methods.

II—PRINCIPLES

1. *General.* A sinusoidal e. m. f. or current may be represented by (see Fig. 1)

$$\underset{\cdot}{E} = e + je'$$

$$\underset{\cdot}{I} = i + ji'$$

where the symbol j ($= \sqrt{-1}$), as it is well known, rotates the quantity before which it is placed through 90 deg. However, since j follows the laws of *ordinary algebra* it is entirely plausible, and interesting to inquire into the meaning of j^n, where n, contrary to common usage is not an integer but any positive or negative number.

Just as j or j^1 indicates rotation through 90×1 deg. and j^3 indicates rotation through 90×3 deg., so $j^{\frac{1}{2}}$ must be interpreted as rotation through $90 \times \frac{1}{2} = 45$ deg. In general Aj^{α} ($\alpha > 0$)

may be interpreted as rotation of the number A through $90 \times \alpha$ deg. or $\frac{\pi}{2}\,\alpha$ radians in the positive or counter-clockwise direction; similarly: $Aj^{-\alpha}$ $(\alpha > 0)$ represents a vector which has been turned through $\alpha\,\frac{\pi}{2}$ radians in the negative direction. Thus the exponent of j may be any number and it indicates the phase relation of the quantity under consideration. For instance, an e. m. f. of E volts and 60 deg. out of phase with the current will be represented according to the above, as $\underset{\cdot}{E} = E\,j^{2/3}$ where $\alpha = (60/90) = 2/3$ and $\underset{\cdot}{I} = I\,j^{\circ} = I$, since j to the zero power = 1, just as for any other algebraic quantity.

If desired the above statements can also be proven by means of De Moivre's theorem, as follows:

$$(\cos\theta + j\sin\theta) = \left(\cos\alpha\frac{\pi}{2} + j\sin\alpha\frac{\pi}{2}\right) \equiv \left(\cos\frac{\pi}{2} + j\sin\frac{\pi}{2}\right)^{\alpha}$$
$$\equiv j^{\alpha}$$

i. e., the operator j^{α} is identical with $(\cos\theta + j\sin\theta)$, where $\theta = \frac{\pi}{2}\,\alpha$.

2. *Multiplication and Division.* As we have seen a vector $\underset{\cdot}{A}$ can be represented as:

$$\underset{\cdot}{A} = a + ja', \text{ or} \tag{7'}$$

$$\underset{\cdot}{A} = A\,j^{\alpha} \tag{7}$$

Similarly a vector $\underset{\cdot}{B}$ can be written as:

$$\underset{\cdot}{B} = b + jb', \text{ or} \tag{8'}$$

$$\underset{\cdot}{B} = B\,j^{\beta} \tag{8}$$

According to the ordinary method,

$$\underset{\cdot}{A}\underset{\cdot}{B} = (ab - a'\,b') + j\,(ab' + a'\,b) \tag{9}$$

NOTE: It will found convenient to denote angles in degrees by α°, β° etc. and the same angles in radians by α', β' etc. In the method herein described α may then be taken as:

$$\frac{\alpha^\circ}{90^\circ} \text{ or } \frac{\alpha'}{\pi/2}\text{; thus } j^{\alpha} = j\,\frac{\alpha^\circ}{90^\circ} = j^{\alpha'/\pi/2}.$$

But $a = A \cos \alpha^\circ, a' = A \sin \alpha^\circ; b = B \cos \beta^\circ$ and $b' = B \sin \beta^\circ$ where $\alpha^\circ = (90\ \alpha)$ deg., and $\beta^\circ = (\beta\ 90)$ deg.

Substituting in equation (**9**) we get:

$$\underset{\cdot}{A}\underset{\cdot}{B} = AB(\cos(\alpha^\circ - \beta^\circ) + j \sin(\alpha^\circ - \beta^\circ))$$

The last expression according to the notation under discussion becomes:

$$\underset{\cdot}{A}\underset{\cdot}{B} = AB\, j^{(\alpha+\beta)} = C j^{\delta}. \qquad (\mathbf{11})$$

Translating (**11**) into words it will be seen that the product of two harmonic quantities represented, as vectors A and B by means of complex quantities of the form (**7**) or (**7′**) and (**8**) or (**8′**) is equal to a new quantity $C = AB$ turned through $\left(\frac{\pi}{2}\,\delta\right)$ radians with respect to the reference axis.

Similarly it will be seen that,

$$\frac{\underset{\cdot}{A}}{\underset{\cdot}{B}} = \frac{A}{B}\, j^{(\alpha-\beta)} \qquad (\mathbf{12})$$

If in equation (**12**) $\underset{\cdot}{A}$ represents an e. m. f. and $\underset{\cdot}{B}$ a current produced by it, their quotient, the impedance of the circuit, is given by:

$$\underset{\cdot}{Z} = Z j^{\gamma}$$

where $Z = A/B$ and $\gamma = (\alpha - \beta)$. In this connection it is of interest to consider in a little detail the meaning of the reciprocal of a plane vector, such as $\underset{\cdot}{Z} = Z j^{\gamma}$

Let $\underset{\cdot}{Y}$ be the reciprocal of $\underset{\cdot}{Z}$; then by definition,

$$\underset{\cdot}{Y}\,\underset{\cdot}{Z} = 1 = (Y j^{\epsilon})\ (Z j^{\gamma})$$

$$= YZ j^{(\epsilon+\gamma)} = 1 j^{\circ}$$

$$i.e.,\ (\epsilon + \gamma) = 0 \text{ or } \epsilon = -\gamma.$$

In short, it is seen that the reciprocal of a vector $\underset{\cdot}{Z} = Z j^{\gamma}$ is a new vector turned through $(-\gamma)\ \frac{\pi}{2}$ radians and having a length equal to $(1/Z)$. The great simplicity of this result is not, of course, unknown in connection with the exponential representation of a vector; but it is not shared with the ordinary notation, and the average student or even engineer is loath to use such expressions as:

$$\underset{\cdot}{Y} = \left(\frac{r}{Z^2} - j\,\frac{X}{Z^2}\right) = (g - jb)$$

since the admittance $\underset{\cdot}{Y}$ in terms of r, x and Z is rather involved and *its physical meaning* is not quite apparent.

In general the product or quotient of any number of vectors can readily be written down:

$$\frac{\underset{\cdot}{A}\underset{\cdot}{B} \text{ etc.}}{\underset{\cdot}{C}\underset{\cdot}{D} \text{ etc.}} = \frac{AB \text{ etc.}}{CD \text{ etc.}}\, j^{(\alpha + \beta \text{ etc.}) - (\gamma + \delta \text{ etc.})} \tag{13}$$

3. *Addition and Subtraction.* Consider two vectors, $\underset{\cdot}{A}$ and $\underset{\cdot}{B}$:

$$\underset{\cdot}{A} = A\, j^{\alpha} = a + ja' \tag{14}$$

$$\underset{\cdot}{B} = B\, j^{\beta} = b + jb' \tag{15}$$

Their sum $\underset{\cdot}{C}$ in terms of rectangular components is:

$$\underset{\cdot}{C} = C j^{\delta} = (a + b) + j\,(a' + b') \tag{16}$$

whence, placing $\alpha' = \frac{\pi}{2}\,\alpha$ and $\beta' = \frac{\pi}{2}\,\beta$,

$$C^2 = A^2 + B^2 + 2\,AB \cos\,(\beta' - \alpha') \tag{17}$$

This follows also directly from elementary trigonometry, (see Fig. 2).

The phase angle $\delta' = \frac{\pi}{2}\,\delta$ can be calculated by means of one of the following expressions.

$$\delta' = \tan^{-1} \frac{A \sin \alpha' + B \sin \beta'}{A \cos \alpha' + B \cos \beta'} \tag{18}$$

$$= \alpha' + 2 \left(\sin^{-1} \sqrt{\frac{S\,(S - B)}{AC}}\right) \tag{19}$$

where $\quad 2\,S = A + B + C.$

Similarly the sum of three or more vectors can be obtained by the use of the above formulas; however, judgment should be exercised in the choice of the method or methods to be used in any given problem in order to simplify calculations as much as possible. Thus in case of more than two vectors it may be more convenient to obtain the resultant by means of the rectangular form of complex quantities.

To find the difference of any two vectors $\underset{\cdot}{A}$ and $\underset{\cdot}{C}$ (see Fig. 3) it may be noted that if $\underset{\cdot}{A} = A\,j^{\delta}$ then $-\underset{\cdot}{A}$ is equal to $\underset{\cdot}{A}\,j^{2}$ and consequently,

$$\underset{\cdot}{B} = C j^{\delta} - A\,j^{\alpha} \qquad \textbf{(20)}$$

$$= C j^{\delta} + A\,j^{\alpha+2} \qquad \textbf{(21)}$$

where $\alpha^{\circ} = 90\,\alpha$ and $(\alpha + 2) = (\alpha^{\circ} + 180)$ deg. Therefore according to equation **(17)** we get:

$$B^{2} = C^{2} + A^{2} - 2\,A C \cos\,(\delta^{\circ} - \alpha^{\circ}) \qquad \textbf{(22)}$$

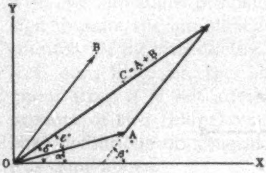

Fig. 2

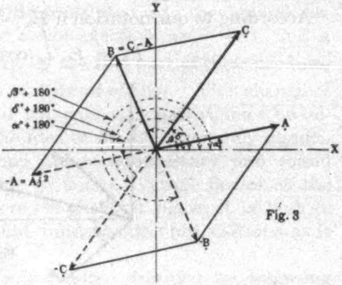

Fig. 3

The phase angle is given by:

$$\beta^{\circ} = \tan^{-1}\frac{C\,\sin\,\delta^{\circ} - A\,\sin\,\alpha^{\circ}}{C\,\cos\,\delta^{\circ} - A\,\cos\,\alpha^{\circ}} \qquad \textbf{(23)}$$

In this connection it may be noted further that, (see Fig. 3)

$$\underset{\cdot}{B} = \underset{\cdot}{C} - \underset{\cdot}{A} = C j^{\delta} + A\,j^{(2+\alpha)} = (C j^{(2+\delta)} + A\,j^{\alpha})\,j^{2}, \qquad \textbf{(24)}$$

or

$$\underset{\cdot}{B}\,j^{+2} = (C j^{2} + \underset{\cdot}{A}) = (\underset{\cdot}{A} - \underset{\cdot}{C}) \qquad \textbf{(25)}$$

4. *General Expression for Power.* The general expression for power which applies to a-c. or d-c. circuits of any wave shape and phase displacement is:

$$P = \frac{1}{T}\int_{0}^{T} e i d t = \frac{1}{\pi}\int_{0}^{\pi} e i d\theta \qquad \textbf{(26)}$$

where e and i are instantaneous values expressed as functions of the time, t, or the time angle, θ, and in the simplest case when e and i are constant, $P = EI$. If, however, e and i are given by a Fourier's series, products of harmonics of different frequencies will contribute nothing, and for the nth harmonic the power P_n will be given by:

$$P_n = \frac{1}{2} (E_{n\,max}\ I_{n\,max} \cos \alpha^\circ) = E_n\, I_n \cos \alpha^\circ \qquad \textbf{(27)}$$

where E_n and I_n are the effective values of the nth harmonic of e. m. f., and current, and $\alpha^\circ = (90\ \alpha)$ deg. is the phase angle between E_n and I_n.

According to our notation if $\underset{\cdot}{E}_n = E_n\, j^\alpha$ and $\underset{\cdot}{I}_n = I_n$ then,

$$P_n = E_n\, I_n \cos \alpha^\circ$$

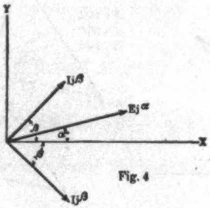

Fig. 4

If in general (see Fig. 4)

$$e = E_{max} \sin (\theta + \alpha^\circ) \qquad \textbf{(28')}$$

$$i = I_{max} \sin (\ \theta \pm \beta^\circ) \qquad \textbf{(29')}$$

or

$$\underset{\cdot}{E} = E j^\alpha \qquad \textbf{(28)}$$

$$\underset{\cdot}{I} = I j^{\pm\beta} \qquad \textbf{(29)}$$

where E and I represent the effective values of E_{max} and I_{max} and $\alpha^\circ = (90\ \alpha)$ deg. and $\beta^\circ = (90\ \beta)$ deg., the power P will be:

$$P = \frac{1}{\pi} \int (ei)\, d\,\theta = \tfrac{1}{2}\ E_{max}\, I_{max} \cos (\alpha^\circ - \beta^\circ) \qquad \textbf{(30)}$$

$$= E\, I \cos (\alpha^\circ - \beta^\circ) \qquad \textbf{(31)}$$

where β may be positive or negative; *i. e.* whether the current be leading or lagging the power is given by equation (**31**).

Comparing this result with the usual rectangular notation we have:

$$P = \frac{1}{\pi}\int (ei)\, d\,\theta = E_n\, I_n\, (\cos\alpha^\circ \cos\beta^\circ + \sin\alpha^\circ \sin\beta^\circ) \qquad \mathbf{(32)}$$

$$= ei \pm e'\, i' \qquad \mathbf{(33)}$$

where $\underset{\cdot}{E}_n = (e_n + je_n')$ and $\underset{\cdot}{I}_n = (i_n \mp ji_n')$

The general expression (**31**) is very simple and it states that the power in any circuit due to any harmonics of the same order is equal to the product of the r. m. s. value of voltage and current into the cosine of their (algebraic) phase difference. As to equation (**32**) it is seen that it can be translated into the general law that the power produced by a voltage $\underset{\cdot}{E} = (e + j\,e')$, and a current, $\underset{\cdot}{I} = (i \pm j\,i')$, is given by the real part of their product, with one important provision of *reversal of sign*. This change of sign impairs the simplicity of the rule although it may be accounted for by introducing the idea of double frequency quantities, etc.; however, this seems rather unnecessary and round about since it is not advisable to define average power as the product of two (plane) vectors, in the first place; it is best to base definitions on general and fundamental propositions as it was done above.

5. *Logarithm of $A\,j^n$.* This is readily obtained by following the rules of algebra according to which:

$$\log\,(A\,j^n) = \log A + \log\,(j^n) \qquad \mathbf{(34)}$$

$$= \log A + n \log\,(j) \qquad \mathbf{(35)}$$

But the logarithm of any complex quantity $a + jb$ is known to be:

$$\log\,(a + jb) = \log\,(\sqrt{a^2 + b^2}) + j\,(\theta + 2\,\pi\, m) \qquad \mathbf{(36)}$$

where $\theta = \tan^{-1}\,(b/a)$ and m is any integer which for simplicity can be taken as zero. Consequently,

$$\log\,(j) = \log\,(j\,1) = j\left(\frac{\pi}{2} + 2\,\pi\, m\right) \qquad \mathbf{(37)}$$

and therefore substituting (**37**) in (**35**):

$$\log\,(A\,j^n) = \log A + j\,\frac{\pi}{2}\,n + 2\,\pi\, m\, n \qquad \mathbf{(38)}$$

where m may be assumed to be zero.

6. *Differentiation.* Assuming again that the operator j^n can be treated as an algebraic quantity we have:

$$\begin{aligned} d\,(\dot{A}) &= d\,(A\,j^n) \\ &= j^n \cdot d\,(A) + A \cdot d\,(j^n) \end{aligned} \qquad \textbf{(39)}$$

Assuming that (j^n) follows the rules of calculus we have:

$$d\,(j^n) = j^n \cdot \log\,(j) \cdot dn \qquad \textbf{(40)}$$

Whence substituting (**37**) and (**40**) in equation (**39**):

$$d\,(\dot{A}) = j^n \cdot d\,A + A\,\frac{\pi}{2} \cdot j^{(n+1)} \cdot dn \qquad \textbf{(41)}$$

The same result can also be obtained as follows:

The differential of a complex quantity is known to be:

$$\begin{aligned} d\,(\dot{A}) &= d\,(a + j\,a') \\ &= d\,(A \cos\,\theta + j\,A \sin\,\theta) \\ &= \cos\,\theta \cdot d\,A - A \cdot \sin\,\theta \cdot d\,\theta \\ &\quad + j\,(\sin\,\theta \cdot d\,A + A \cdot \cos\,\theta \cdot d\,\theta) \\ &= (\cos\,\theta + j\,\sin\,\theta)\,d\,A \\ &\quad + A\,d\,\theta\,j\,(\cos\,\theta + j\,\sin\,\theta) \end{aligned}$$

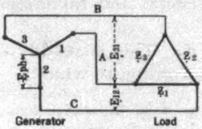

Fig. 5

It is easy, by substituting j^n for the operator $(\cos\,\theta + j\,\sin\,\theta)$, where $\theta = \dfrac{\pi}{2}\,n$, to obtain equation (**41**).

Or again, if desired the exponential form can be used and by substituting j^n for $e^{j\theta}$ in

$$d\,(A e^{j\theta}) = e^{j\theta}\,.\,d\,A + A\,e^{j\theta}\,j\,.\,d\,\theta \qquad \textbf{(42)}$$

expression (**41**) be derived.

III—ILLUSTRATIVE PROBLEMS

In order to illustrate the use and application of the method just described a few simple examples will be considered.

(1)A Y-connected generator feeds an unbalanced Δ-connected

DATA:

Phase Voltages of Generator:

A	B	C	D
$\underset{\cdot}{E}_{1ph} = E_{ph}$	$= \left\{\begin{matrix} e_{ph} \\ e_1 \end{matrix}\right.$	$= E_{ph1}$	$= E_{ph}$
$\underset{\cdot}{E}_{2ph} = E_{ph} j^{-\frac{4}{3}} = E_{ph} j^{-\frac{120^\circ}{90^\circ}}$	$= \left\{\begin{matrix} -0.5\, e_{ph} - j\, 0.866\, e_{ph} \\ e_2 + j\, e'_2 \end{matrix}\right.$	$= E_{ph}\left(\cos\frac{2\pi}{3} - j\sin\frac{2\pi}{3}\right)$	$= E_{ph}\, \epsilon^{-j\frac{2\pi}{3}}$
$\underset{\cdot}{E}_{3ph} = E_{ph} j^{-\frac{8}{3}} = E_{ph} j^{-\frac{240^\circ}{90^\circ}}$	$= \left\{\begin{matrix} -0.5\, e_{ph} + j\, 0.866\, e_{ph} \\ e_3 + j\, e'_3 \end{matrix}\right.$	$= E_{ph}\left(\cos\frac{4\pi}{3} - j\sin\frac{4\pi}{3}\right)$	$= E_{ph}\, \epsilon^{-j\frac{4\pi}{3}}$

Impedances of Load:

$$Z_1\, j^{\alpha} = r_1 + jx_1 = Z_1 (\cos \alpha' + j \sin \alpha') = Z_1\, \epsilon^{j\alpha'}$$

$$Z_2\, j^{\beta} = r_2 + j\, x_2 = Z_2 (\cos \beta' + j \sin \beta') = Z_2\, \epsilon^{j\beta'}$$

$$Z_3\, j^{\gamma} = r_3 + j\, x_3 = Z_3 (\cos \gamma' + j \sin \gamma') = Z_3\, \epsilon^{j\gamma'}$$

where,

$$Z_1 = \sqrt{r_1^2 + x_1^2}; \quad \alpha' = \frac{\pi}{2}\, \alpha = \tan^{-1}\left(\frac{x_1}{r_2}\right)$$

Similarly for the others.

SOLUTION:

Line voltages at load:

A	B	C	D
$\underset{\cdot}{E}_{12} = E j^{\frac{1}{3}} = E j^{\frac{30^\circ}{90}}$	$= \left\{\begin{matrix} e_{12} + j\, e'_{12} \\ 0.866\, E + j\, 0.5\, E \end{matrix}\right.$	$= E \left(\cos\frac{\pi}{6} + j\sin\frac{\pi}{6}\right)$	$= E\, \epsilon^{j\frac{\pi}{6}}$
$\underset{\cdot}{E}_{23} = E j^{-1} = E j^{-\frac{90^\circ}{90^\circ}}$	$= \left\{\begin{matrix} -j\, e'_{23} \\ -j\, E \end{matrix}\right.$	$= E(-j)$	$= E\, \epsilon^{-j\frac{\pi}{2}}$
$\underset{\cdot}{E}_{31} = F^{5/3} = E j^{\frac{150^\circ}{90^\circ}}$	$= \left\{\begin{matrix} e_{31} + j\, e'_{31} \\ -0.866\, E + j\, 0.5\, E \end{matrix}\right.$	$= E \left(\cos\frac{5\pi}{6} + j\sin\frac{5\pi}{6}\right)$	$= E\, \epsilon^{j\frac{5\pi}{6}}$

where $E = \sqrt{3}\, E_{ph}$.

load as shown in Fig. 5. To find the respective phase and line currents, voltages, phase angles and power.

This problem will be solved by the use of complex quantities and the exponential form as follows:

A —Notation discussed above.
B —The usual reactangular form.
C —The usual polar form.
D —The exponential form.

Phase currents of load:

$$\underset{\cdot}{I}_{1ph} = \frac{E}{Z_1}\, j^{(\frac{1}{3}-\alpha)} = \frac{(e_{12} + j\, e'_{12})\,(r_1 - j\, x_1)}{Z_1^2}$$

$$= \frac{E}{Z_1}\left[\cos\left(\frac{\pi}{6} - \alpha'\right) + j \sin\left(\frac{\pi}{6} - \alpha'\right)\right] = \frac{E}{Z_1}\,\epsilon^{j\left(\frac{\pi}{6} - \alpha'\right)}$$

$$\underset{\cdot}{I}_{2ph} = \frac{E}{Z_2}\, j^{-(1+\beta)} = \frac{(-j\, e'_{23})\,(r_2 - j\, x_2)}{Z_2^2}$$

$$= \frac{E}{Z_2}\left[-\sin\beta' + j\cos\beta'\right] = \frac{E}{Z_2}\,\epsilon^{-j\left(\frac{\pi}{2} + \beta'\right)}$$

$$\underset{\cdot}{I}_{3ph} = \frac{E}{Z_3}\, j^{(5/3-\gamma)} = \frac{(e_{31} + j\, e'_{31})\,(r_3 - j\, x_3)}{Z_3^2}$$

$$= \frac{E}{Z_3}\left[\cos\left(\frac{5\pi}{6} - \gamma'\right) + j\sin\left(\frac{5\pi}{6} - \gamma'\right)\right] = \frac{E}{Z_3}\,\epsilon^{j\left(\frac{5\pi}{6} - \gamma'\right)}$$

Line Currents A

$$\underset{\cdot}{I}_{A} = (\underset{\cdot}{I}_{1ph} - \underset{\cdot}{I}_{3ph})$$

$$= j^{\delta}\left[I^2_{1ph} + I^2_{3ph} - 2\, I_{1ph}\, I_{3ph} \cos\left(\frac{5\pi}{6} - \gamma' - \frac{\pi}{6} + \alpha'\right)\right]^{\frac{1}{2}}$$

$$\underset{\cdot}{I}_{B} = (\underset{\cdot}{I}_{3ph} - \underset{\cdot}{I}_{2ph})$$

$$= j^{\theta}\left[I^2_{2ph} + I^2_{3ph} - 2\, I_{2ph}\, I_{3ph} \cos\left(\frac{5\pi}{6} - \gamma' + \frac{\pi}{2} + \beta'\right)\right]^{\frac{1}{2}}$$

$$J_{C} = (\underset{\cdot}{I}_{2ph} - \underset{\cdot}{I}_{1ph})$$

$$= j^{\lambda}\left[I^2_{1ph} + I^2_{2ph} - 2\, I_{1ph}\, I_{2ph} \cos\left(\frac{\pi}{6} - \alpha' + \frac{\pi}{2} + \beta'\right)\right]^{\frac{1}{2}}$$

B.

$$\underset{\cdot}{I}_{\mathrm{A}} = (\underset{\cdot}{I}_{1ph} - \underset{\cdot}{I}_{3ph}) = (i_{1ph} - i_{3ph}) + j\,(i'_{ph} - i'_{3ph})$$

$$\underset{\cdot}{I}_{\mathrm{B}} = (\underset{\cdot}{I}_{3ph} - \underset{\cdot}{I}_{2ph}) = (i_{3ph} - i_{2ph}) + j\,(i'_{3ph} - i'_{2ph})$$

$$\underset{\cdot}{I}_{\mathrm{C}} = (\underset{\cdot}{I}_{2ph} - \underset{\cdot}{I}_{1ph}) = (i_{2ph} - i_{1ph}) + j\,(i'_{2ph} - i'_{1ph})$$

where,

$$(i_{1ph} + j\,i'_{1ph}) = [(e_{12}\,r_1 + e'_{12}\,x_1) + j\,(e'_{12}\,r_1 - e_{12}\,x_1)]\,Z_1^{-2}$$

$$(i_{2ph} + j\,i'_{2ph}) = [-\,e'_{23}\,x_2 + j\,e'_{23}\,r_2]\,Z_2^{-2}$$

$$(i_{3ph} + j\,i_{3ph}) = [(e_{31}\,r_3 + e_{31}\,x_3) + j\,(e'_{31}\,r_3 - e_{31}\,x_3)]\,Z_3^{-2}$$

C.

$$\underset{\cdot}{I}_{\mathrm{A}} = \left[\frac{E}{Z_1}\cos\left(\frac{\pi}{6} - \alpha'\right) - \frac{E}{Z_3}\cos\left(\frac{\pi}{6} - \gamma'\right)\right] + j\left[\frac{E}{Z_1}\sin\left(\frac{\pi}{6} - \alpha'\right) - \frac{E}{Z_3}\sin\left(\frac{5\,\pi}{6} - \gamma'\right)\right]$$

$$\underset{\cdot}{I}_{\mathrm{B}} = \left[\frac{E}{Z_3}\cos\left(\frac{5\,\pi}{6} - \gamma'\right) - \frac{E}{Z_2}\sin\beta'\right] + j\left[\frac{E}{Z_3}\sin\left(\frac{\pi}{6} - \gamma'\right) + \frac{E}{Z_2}\cos\beta'\right]$$

$$\underset{\cdot}{I}_{\mathrm{C}} = \left[\frac{E}{Z_2}\sin\beta' - \frac{E}{Z_1}\cos\left(\frac{\pi}{6} - \alpha'\right)\right] - j\left[\frac{E}{Z_2}\cos\beta' + \frac{E}{Z_1}\sin\left(\frac{\pi}{6} - \alpha'\right)\right]$$

In case of method D in order to carry on actual computation for I_{A}, I_{B} and I_{C} it is necessary to make recourse to one of the other methods.

In regard to the expression given under B and C, it may be noted that the square root of the sums of the squares of the two components has to be taken in order to find the magnitude of the line currents I_{A}, I_{B} and I_{C}.

Phase angles of the line currents: A.

$$\delta^\circ = \tan^{-1}\frac{I_{1ph}\sin\left(\frac{\pi}{6} - \alpha'\right) - I_{3ph}\sin\left(\frac{5\,\pi}{6} - \gamma'\right)}{I_{1ph}\cos\left(\frac{\pi}{6} - \alpha'\right) - I_{3ph}\cos\left(\frac{5\,\pi}{6} - \gamma'\right)}$$

$$\theta^\circ = \tan^{-1} \frac{I_{3ph} \sin\left(\frac{5\pi}{6} - \gamma'\right) + I_{2ph} \sin\left(\frac{\pi}{2} + \beta'\right)}{I_{3ph} \cos\left(\frac{5\pi}{6} - \gamma'\right) - I_{2ph} \cos\left(\frac{\pi}{2} + \beta'\right)}$$

$$\lambda^\circ = \tan^{-1} \frac{- I_{2ph} \sin\left(\frac{\pi}{2} + \beta'\right) - I_{1ph} \sin\left(\frac{\pi}{6} - \alpha'\right)}{I_{2ph} \cos\left(\frac{\pi}{2} + \beta'\right) - I_{1ph} \sin\left(\frac{\pi}{6} - \alpha'\right)}$$

where $\delta^\circ = 90\,\delta$ degrees, and similarly for the others.

B

$$\delta^\circ = \tan^{-1} \frac{i'_{1ph} - i'_{3ph}}{i_{1ph} - i_{3ph}} \qquad \theta^\circ = \frac{i'_{3ph} - i'_{2ph}}{i_{3ph} - i_{2ph}}$$

$$\lambda^\circ = \tan^{-1} \frac{i'_{2ph} - i_1{}'_{ph}}{i_{2ph} - i_{1ph}}$$

C

$$\delta^\circ = \tan^{-1} \frac{\frac{E}{Z_1} \sin\left(\frac{\pi}{6} - \alpha'\right) - \frac{E}{Z_3} \sin\left(\frac{5\pi}{6} - \gamma'\right)}{\frac{E}{Z_1} \cos\left(\frac{\pi}{6} - \alpha'\right) - \frac{E}{Z_3} \cos\left(\frac{5\pi}{6} - \gamma'\right)}$$

similarly for θ° and λ°.

Power at the load: A

$$P_{1ph} = I^2{}_{1ph} Z_1 \cos \alpha^\circ \text{ or } P_{1ph} = E\, I_{1ph} \cos (30^\circ - \alpha^\circ - 30^\circ)$$

$$P_{2ph} = I^2{}_{2ph} Z_2 \cos \beta^\circ \text{ or } P_{2ph} = E I_{2ph} \cos (-\,150^\circ - \beta^\circ - 150^\circ$$

$$P_{3ph} = I^2{}_{3ph} Z_3 \cos \gamma^\circ \text{ or } P_{3ph} = E I_{3ph} \cos (150^\circ - \gamma^\circ - 150^\circ)$$

B

$$P_{1ph} = I^2{}_{1ph}\, r_1 \text{ or } P_{1ph} = e_{12}\, i_{1ph} + e'_{12ph}\, i'_{1ph}.$$

$$P_{2ph} = I^2{}_{2ph}\, r_2 \text{ or } P_{2ph} = -\, e'_{23}\, i'_{2ph}$$

$$P_{3ph} = I^2{}_{3ph}\, r_3 \text{ or } P_{3ph} = e_{31}\, i_{3ph} + e'_{31}\, i'_{1ph}$$

C and D

$$P_{1ph} = \frac{E^2}{Z_1} \cos \alpha^\circ \quad P_{2ph} = \frac{E^2}{Z_2} \cos \beta^\circ \quad P_{3ph} = \frac{E^2}{Z_3} \cos \gamma^\circ$$

which are, of course, similar to the expression given for method A.

Numerical example: Let $E = 100$; $E_{ph} = \dfrac{100}{\sqrt{3}}$;

$$\text{and, } \underset{\cdot}{Z}_1 = 1.\ j^{\frac{45^\circ}{90^\circ}} \qquad 0.707 + j\,0.707$$

$$\underset{\cdot}{Z}_2 = 1.2\, j^{\frac{20^\circ}{90^\circ}} \qquad = \quad 1.128 + j\,0.408$$

$$\underset{\cdot}{Z}_3 = 1.3\, j^{-\frac{10^\circ}{90^\circ}} \qquad = 1.28 \quad - j\,0.226$$

then,

$$\underset{\cdot}{I}_{1ph} = 100\, j^{-\frac{15^\circ}{90^\circ}} \qquad \underset{\cdot}{I}_{2ph} = 83.3\, j^{-\frac{110^\circ}{90^\circ}} \qquad \underset{\cdot}{I}_{3ph} = 77\, j^{\frac{160^\circ}{90^\circ}}$$

$$I_A \quad = [\overline{100}^2 + \overline{77}^2 - 200 \times 77 \cos 175^\circ]^{\frac{1}{2}} = 177 \text{ amperes.}$$

$$I_B \quad = [\overline{83.3}^2 + \overline{77}^2 - 2 \times 83.3 \times 77 \cos 270^\circ]^{\frac{1}{2}} = 114 \text{ amperes.}$$

$$I_C \quad = [\overline{83.3}^2 + 100^2 - 200 \times 83.3 \cos 95^\circ]^{\frac{1}{2}} = 137 \text{ amperes.}$$

$$\delta^\circ = 18^\circ = \delta\,(90^\circ);\ \delta = 0.2$$

$$\theta^\circ = 112.8^\circ = \theta\,(90^\circ);\ \theta = 1.255$$

$$\lambda^\circ = 202.8^\circ = \lambda\,(90^\circ)\,\lambda = 2.259$$

Power at load:

$$P_1 = 100 \times 100 \times \cos 45^\circ$$
$$= 1 \times \overline{100}^2 \times \cos 45^\circ \qquad = 7070 \text{ watts}$$

$$P_2 = 100 \times 83.4 \times \cos 20^\circ$$
$$= \overline{83.4}^2 \times 1.12 \times \cos 20^\circ \qquad = 7860 \text{ watts}$$

$$P_3 = 100 \times 77 \times \cos 10^\circ$$
$$= \overline{77}^2 \times 1.3 \times \cos 10^\circ \qquad = 7600 \text{ watts}$$

Total power at load = 22,520 watts.

Power at generator:

$$P_1 = 177 \times \frac{100}{\sqrt{3}} \times \cos 18^\circ = 9710.$$

$$P_2 = 114 \times \frac{100}{\sqrt{3}} \times \cos 120^\circ = 6520.$$

$$P_3 = 137 \times \frac{100}{\sqrt{3}} \times \cos 240^\circ = 6290.$$

Total power at generator = 22,520 watts.
The vector diagram is shown in Fig. 6.

2. A load having a variable power factor and consuming a constant voltage is supplied through an inductive line whose characteristics are: $(r + jx) = \dot{Z} = Zj^{\alpha}$. To investigate the effect of leading and lagging current on the generator voltage.

Taking the load voltage as the reference vector, the generator voltage, E_g, is:

$$E_g = e + Ij^{\pm\beta}.\, Zj^{\alpha} = e + IZ\, j^{(\alpha \pm \beta)}$$

where the positive sign refers to leading and the negative sign to lagging current.

Inasmuch as we are dealing with vector addition of a quantity (IZ), making $(\alpha^\circ \pm \beta^\circ)$ degrees with a horizontal line (e) volts, a little consideration will show that for any given value of β° the resultant E_g will be larger when β° is negative, *i. e.* when the load is inductive than when the load is condensive. Indeed it is not difficult to form a mental picture of the sum of the two vectors, e and $(IZ)j^{(\alpha \pm \beta)}$, and see that when $(\alpha^\circ \pm \beta^\circ) = 0$, E_g is maximum, and when

$$(\alpha^\circ \pm \beta^\circ) = 90^\circ \; E_g \text{ is minimum.}$$

Suppose now we prove this elementary but fundamental proposition by means of the usual rectangular form of complex quantities:

$$E_g = [(e + ir - i'x)^2 + (i'r + ix)^2]^{\frac{1}{2}}, \text{ for leading current.}$$

$$E'_g = [(e + ir + i'x)^2 + (ix - i'r)^2]^{\frac{1}{2}} \text{ for lagging current.}$$

It is not apparent by comparing these equations to see whether $E_g > E_g'$ or vice-versa.

3. Finally consider the calculation of the characteristics of a long transmission line with distributed inductance and capacity. It is known that the voltage and current at any point along the line, at a distance l from the receiving end, are given by the following expressions:

$$\underset{\cdot}{E}_1 = \underset{\cdot}{E}_r\,(1+ \underset{\cdot}{Z}\underset{\cdot}{Y}/2 + \underset{\cdot}{Z}^2\underset{\cdot}{Y}^2/24) + \underset{\cdot}{Z}\underset{\cdot}{I}_r\,(1+ \underset{\cdot}{Z}\underset{\cdot}{Y}/6 + \underset{\cdot}{Z}^2\underset{\cdot}{Y}^2/120)\,..$$

$$\underset{\cdot}{I}_1 = \underset{\cdot}{I}_r\,(1+ \underset{\cdot}{Z}\underset{\cdot}{Y}/2 + \underset{\cdot}{Z}^2\underset{\cdot}{Y}^2/24) + \underset{\cdot}{Y}\underset{\cdot}{I}_r\,(1+ \underset{\cdot}{Z}\underset{\cdot}{Y}/6 + \underset{\cdot}{Z}^2\underset{\cdot}{Y}^2/240)\,..$$

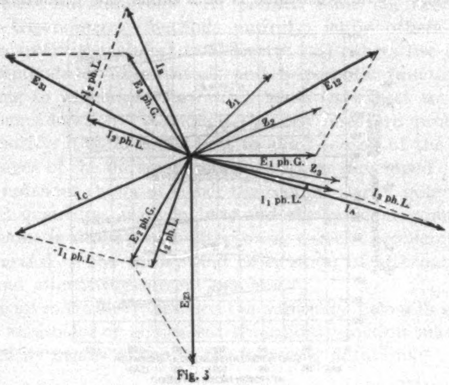

Fig. 3

Generator phase voltages, E_1, *ph. G.* etc., line voltages, E_{12}, etc. are to same scale. Phase currents of load, I_1*ph L.* etc., and line currents, I_A etc. are to same scale which is different from the voltage scale.

where Z and Y are the impedance and admittance of the length of the line under consideration, and the subscript refers to the receiving end. These equations are fairly long for purposes of calculation on account of the many multiplications involved furthermore computations become rather tedious owing to the fact that ordinarily, either the real or imaginary components of some of the quantities involved are very small, but still cannot be neglected. These objections will remain true, although to a lesser degree, even when the equations are simplified by dropping the terms containing Z^2 and Y^2. For the sake of comparison the

e. m. f. equation is given in the usual notation and in the one discussed above:

$$E_1 = (e_r + je'_r)\,[1 + (r + jx)\,(g + jb)/2 + (r + jx)\,(i_r + ji_r')]$$

$$E_1 = E_r j^{\delta} + E_r Z Y j^{(\alpha + \beta + \delta)} + I_r Z j^{(\alpha + \gamma)}$$

As an example the curves in Fig. 7 give the characteristics of a transmission line 100 miles long and delivering 20,000 kw. at 100 kv. (or $100/\sqrt{3}$ to neutral) with a periodicity of 25 cycles per second. The line consists of two No. 00 B. & S. aluminum conductors in parallel, spaced 7 ft. apart and strung on separate steel towers. The resistance is 32.2 ohms, the inductive reactance is 4376 ohms and the condensive reactance is 0.664 ohms per conductor.

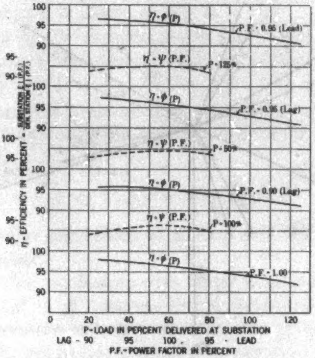

FIG. 7

The calculations are too lengthy to be given in detail and would be of little value since nothing can take the place of testing for ones' self, by actual calculations, the advantages and disadvantages of the different methods.

IV—CRITICAL RÉSUMÉ AND SUMMARY

It has been shown that without any radical modification of the present day method of alternating-current technology it is possible to deal in *calculations* directly with vectors in a simple manner by using the polar form of complex quantities involving the operator $j^{\alpha} = (\sqrt{-1})^{\alpha}$, which indicates rotation through 90 α deg. in the positive direction. Thus,

$$\underset{\cdot}{E} = Ej^{\alpha}\text{, in the polar form given herein;}$$

$$\underset{\cdot}{E} = e + je'\text{, in the rectangular form.}$$

The choice of mathematical methods and notations is necessarily to a certain extent, influenced by personal tastes and it is not practicable to give any general rules as to when the notation given herein, either by itself or in combination with others, will prove most advantageous. At present some engineers prefer to use trigonometric methods entirely, while others employ complex quantities almost exclusively; still others use either of these methods or exponentials and hyperbolic functions, etc. according to whichever they think lends itself best to the case under consideration. Although the last ones are probably in the minority, it is no doubt best to avail oneself of the peculiar advantages of the different notations so far developed.

The judicious choice of either the rectangular or polar form of complex quantities as given here and the judicious combination of the same in dealing with alternating-current problems will be found useful in the theory and calculation of alternating currents and alternating-current machinery.

For convenience of reference the summary below is given:

I. A sinusoidal or equivalent sinusoidal function may be represented by means of one of the following notations:[2]

$$(1)\quad \underset{\cdot}{A} = A\,j^{\alpha}$$

$$(2)\quad \underset{\cdot}{A} = a + ja'$$

$$(3)\quad \underset{\cdot}{A} = A\,(\cos\alpha^\circ + j\sin\alpha^\circ)$$

$$(4)\quad \underset{\cdot}{A} = A\,e^{j\alpha'}$$

$$(5)\quad \underset{\cdot}{A} = A\underline{/\alpha^\circ}$$

Where $\frac{\pi}{2}\,\alpha = \alpha'$ radians and $\alpha\,90 = \alpha^\circ$ deg.

---

[2] The exponent of j in **(1)** is a number; the exponent of **(4)** must be j (radians); and the angle in **(3)** and **(5)** may be expressed in radians or degrees. In this connection it may be noted that **(5)** is more of a ***symbol*** than a ***mathematical notation.***

II. The product of any number of vectors is:

$$\underset{\cdot}{B} = \underset{\cdot}{A}\underset{\cdot}{B}\underset{\cdot}{C} \text{ etc.} = (ABC \text{ etc.}) \left(j^{(\alpha + \beta + \gamma \text{ etc.})} \right)$$

III. The quotient of any number of vectors is:

$$\frac{\underset{\cdot}{A}\underset{\cdot}{B} \text{ etc.}}{\underset{\cdot}{C}\underset{\cdot}{D} \text{ etc.}} = \frac{AB \text{ etc.}}{CD \text{ etc.}} \; j^{(\alpha + \beta \text{ etc.}) - (\gamma + \delta \text{ etc.})}$$

The reciprocal of a vector Zj^{α} is $(I/Z)\, j^{-\alpha}$

IV. The sum of two vectors is:

$$A\, j^{\alpha} + B\, j^{\beta} = [A^2 + B^2 + 2\, AB \cos (\alpha^\circ - \beta^\circ)]^{\frac{1}{2}}\, j^{\delta}$$

where,

$$\delta^\circ = \tan^{-1} \frac{A \sin \alpha^\circ - B \sin \beta^\circ}{A \cos \alpha^\circ - B \cos \beta^\circ} = (90\delta) \text{ and } \alpha^\circ = (\alpha\, 90);$$

$$\beta^\circ = (\beta\ 90)$$

V. The difference of two vectors is:

$$Aj^{\alpha} - B\, j^{\beta} = [A^2 + B^2 - 2\, AB \cos (\alpha^\circ - \beta^\circ)]^{\frac{1}{2}}\, j^{\delta}$$

where,

$$\delta^\circ = \tan^{-1} \frac{A \sin \alpha^\circ - B \sin \beta^\circ}{A \cos \alpha^\circ - B \cos \beta^\circ}$$

VI. The power in a circuit due to a current $Ij^{\pm\beta}$ propelled by an e.m.f. $E\, j^{\alpha}$ is:

$$P = EI \cos (\alpha^\circ - \beta^\circ)$$

VII. The differential of Aj^{α} is:

$$d\, (A\, j^{\alpha}) = j^{\alpha} (dA + A\, j\, \frac{\pi}{2} \,.\, d\,\alpha)$$

VIII. The logarithm of $A\, j^{\alpha}$ is:

$$\log\, (A\, j^{\alpha}) = \log A + j \left(\frac{\pi}{2}\ \alpha + 2\, \pi\, m \right)$$

where *m* may be taken as zero.

IX. Some other expressions of interest are as follows:

1. $\underset{\cdot}{A} = A\,j^{\alpha}$ or strictly $\underset{\cdot}{A} = A\,j^{\alpha+4m}$, where m may be taken as zero, this being the usual practise in all similar cases. For instance, $1/2 = \sin \pi/6$ or strictly $1/2 = \sin (\pi/6 + 2\,\pi\,m)$

2. $(Aj^{\alpha})^m = A^m\,(j^{m\alpha})$. Similarly,

$$\sqrt[m]{Aj} = A^{1/m}.\,j^{\alpha/m}$$

3. $j^{\alpha} = e^{j\,\alpha\frac{\pi}{2}} = (\cos \alpha^{\circ} + j\,\sin\,\alpha^{\circ})$, where $(\alpha \times 90) = (\alpha^{\circ})$ deg.

Therefore, $j = \sqrt{-1} = e^{j\,\pi/2}$

4. $$\log j = \log\,(e^{j\,\pi/2}) = j\,\frac{\pi}{2}$$

$$\log j^{\alpha} = \log\,(e^{j\,\alpha\,\pi/2}) = j\,\alpha\,\frac{\pi}{2}$$

In conclusion the writer wishes to thank Mr. W. C. Graustein, of the department of mathematics of the Rice Institute, for valuable criticisms and suggestions.

SHORT BIBLIOGRAPHY

TRANSACTIONS OF A. I. E. E.

Symbolic representation of general alternating waves and double-frequency vector products. C. P. Steinmetz, vol. 16, pp. 269, 1899.

Application of hyperbolic analysis to the discharge of a condenser. Alex. Macfarlane. Vol. 14, pp. 169. 1897.

Impedance. By A. E. Kennelly, vol. 10, pp. 179. 1893.

A trigonometric method for the solution of alternating-current problems H. Pender. A. I. E. E. TRANS., Vol. 27. pp. 1397. 1908.

SCIENCE ABSTRACTS

No. abstract; vol. 1, 1898.

291. Use of imaginary quantities in alternating-current problems. P. Janet, *Ecl. Electr.* 15 pp., 529-531. 1897.

292. Alternating-current problems—C. F. Guilbert. *Ecl. Electr.* 14 pp., 69-70. 1898.

403. Application of vector algebra to alternating currents. W. G. Rhodes, *Elect. Review* 44, pp. 22-25; 54-56; 90-92. 1898.

524. Graphical methods in alternating-current problems. C. E. Guye, *Ecl. Electr.* 14, pp. 321-325. 1898.

796. Graphical study of alternating currents. C. E. Guye. *Ecl. Electr.* 14, pp. 503-508. 1898.

798. Application of imaginary quantities to transformer equations. J. B. Pomey. *Ecl. Electr.* 15, pp. 16-18. 1898.

1162. Graphical methods in alternating-current problems. C. E. Guye. *Ecl. Electr.* 15, pp. 363-369. 1898.

1240. Imaginary electrical quantities. H. Pellat. *Ecl. Electr.* 15, pp. 221-228. 1898.

No. of Abstract; Vol. 2, 1899.

123. Graphical study of alternating-currents. C. E. Guye, *Ecl. Electr.* 16, pp. 397-405. 1898.

317. Alternating-current problems. T. R. Lyle, *Electrician* 41, pp. 816-818. 42—pp. 72-74; 148-151. 1898.

No. of Abstract. Vol. 3, 1900.

194. Alternating-current theory. C. P. Steinmetz, 1899.

1093. Alternating-current diagrams. R. A. Philip, *Elect. World and Engin.* 34, pp. 970-972. 1899.

1667. Imaginary quantities and periodic functions. C. F. Gilbert, *Ecl. Electr.* 22, pp. 405-414. 1900.

No. of Abstract. Vol. 4. 1901.

153. Graphical methods applied to problems in polyphase distribution. *Elektr. Zeitschr.*, 21, pp. 733-735. Aug. 30. pp. 749-752. Sept. 6.

No. of Abstract. Vol. 5, 1902.

1108. Limitations of graphics in electrical theory. A Russell. *Elec. Engin. Journal* 31, pp. 438-441. 1902.

No. of Abstract. Vol. 6, Section A. 1902.

103. Vector diagrams for distorted wave shapes. J. Teichmuller. *Zeitschr.* 3, pp. 442-449. 1902.

1066. Graphical treatment of alternating-current problems. E. Orlich. *Elektrotechn. Zeitschr.* 24, pp. 59-60. 1903.

No. of Abstract. Vol. 7, Section A. 1903.

2714. Network problems. Graphical solution of. E. Aoyagi. *Coll. Sci. and Engin.* 1.1. pp. 40-54. 1903.

No. of Abstract. Vol. 11, Section B. 1908.

758. Methods of solving alternating-current problems. H. Pender *Amer. Inst. Elect. Engin. Trans. Vol.* 27, pp. 1397. 1908.

No. of Abstract. Vol. 12, Section B. 1909.

634. Power Factors. G. Campos. *Atti. dell. Assoc. Elettr. Ital.* 13, pp. 197-210. 1909.

No. of Abstract. Vol. 13, Section B. 1910.

34. Vector representation of wave forms. B. Arakawa. *Phy. Rev.* 29, pp. 409-431. 1909.

646. Vector power in alternating circuits. A. E. Kennelly. *Amer. Inst. Elect. Engin. Trans. Vol.* 29, pp. 1233. 1910.

1051. Vector power in alternating circuits. A. E. Kennelly, *Amer. Inst. Elect. Engin. Trans. Vol.* 29, pp. 1233. 1910.

No. of Abstract. Vol. 16, Section B, 1913.

1067. Direction of rotation and phase lead in alternating-current diagrams. *Elektrotechn. Zeitschr.* 34, pp. 924-927. 1913.

TEXT BOOKS

The application of hyperbolic functions to electrical engineering problems. A. E. Kennelly. (A bibliography bearing on the subject will be found at the end of this work.)

Vector Analysis and Quaternions. Alex. Macfarlane. (Mathematical monographs) edited by M. Merriman and S. Woodward.

DISCUSSION ON "APPLICATION OF A POLAR FORM OF COMPLEX QUANTITIES TO THE CALCULATION OF A-C. PHENOMENA" (DIAMANT), CLEVELAND, OHIO, JUNE 30, 1916.

Alexander Gray: Every September, before I meet my classes, I have to review the subject of complex quantities as applied to the solution of the problems in electrical engineering because, during the rest of the year, I never have occasion to use this method in my own work.

I am afraid that, in some of our schools, the use of this method is carried to extremes. An induction motor for example becomes a curly line and is called $r + j x$ but, while the solutions obtained are elegant, the student does not always know what they mean nor does he obtain such an idea of the operation of the machine as to argue regarding its characteristics when away from his formulas.

It is true that in circuit work solutions may more readily be obtained by the use of complex quantities than by other methods but I find that if the problem is not in the book the student is not satisfied with the solution until he has checked it by vector diagrams and trigonometry.

Unfortunately the average student is not equipped with sufficient mathematics to understand what he is doing when he uses the methods of Dr. Steinmetz or this elegant method now suggested by Prof. Diamant.

E. E. F. Creighton: I think it is very exceptional indeed that mathematics is used after leaving college. Men come to me, who have been out of college a year, and are unable to use the mathematics which they learned there. Of course, there are exceptions. I should say this condition is somewhat a reflection on the methods of teaching mathematics. There are a good many things interesting about mathematics, although you would never know it by the way it is taught.

It happens that other methods seem to be favored in the industrial concerns. One can get a solution of a problem in general more quickly and better by some non-mathematical method. I must say, however, I have had several men with me who have been of the greatest help to me by being able to use freely the mathematics favored by Dr. Steinmetz.

May I ask Mr. Diamant just where is a good place to apply this mathematical method?

John B. Whitehead: I want to ask Professor Gray what is his explanation and justification of the original vector diagram. How can he give the vector diagram to a student, without taking it back somewhere to a mathematical expression, and if to a mathematical expression, why not to the polar diagram? I take it that he will agree with me that there is no justification for the crank diagram. Therefore, I think this paper should be of some interest to those of us who have to teach.

I do not suppose Mr. Diamant will claim that this paper should be used by the work-a-day engineer. In fact I question whether Dr. Steinmetz, although he has taken his own method so far into the range of application, would maintain that to be its end and object. The great debt we owe to Dr. Steinmetz is for having developed a method which is so universally applicable in the teaching of principles. I do not agree that the exponential expression is the proper one for the fundamental instruction, and I think the polar diagram, taking its origin from the exponential expression, and the method of division into two components, is the most valuable. The method of Dr. Steinmetz in the division into two components seems to me to fail at the problem of power expression—the product of two vectors. The present paper offers something to fill this vacancy, and hence merits attention.

E. H. Colpitts: Referring to Professor Gray's question inquiring as to the usefulness of Dr. Steinmetz's mathematics, I feel safe in saying that the telephone engineer at least finds these methods of very substantial value in handling many problems.

N. S. Diamant: I think the general trend of remarks was about complex quantities in general, rather than the particular method given in the paper and showed a little prejudice in connection with the question. Probably this is mainly due to the fact that some persons want to use nothing but complex quantities, while a great many others will have nothing to do with them.

In regard to the question raised as to the usefulness of mathematics I think we must recognize that mathematics in engineering is very useful as a tool. I could give actual examples where great advance has been made by the use of mathematics, and very wonderful scientific and practical work has been produced by the use of it. After all, as I say, I am not here to defend mathematics. I think the trouble comes in when we use too much, or try to cover up our ignorance by the use of mathematics, and that is done quite often; you will find it in many so-called text-books.

E. E. F. Creighton: I asked what your particular method of mathematics is, how you could apply it, in what particular way could you apply it.

N. S. Diamant: I have indicated that in the summary of the paper. However, as it has been brought out by Prof. Gray—the choice of method depends considerably upon the type of mind. Some persons like one method, and some persons like another; one is just as good as the other.

Another point of interest that Prof. Gray brought up was that the student, when he is working with complex quantities, is not entirely satisfied, and does not well understand the problem until he has translated it graphically by means of a vector diagram. In that connection I would like to add that the advantage of my method is that it is a better mathematical shorthand by means of which to visualize vector relationships. This is not easy to do in complicated vector diagrams, when you have to deal with the components; when for example, we have $e + j\,e$ equal to E, or similar expressions. It is easier to visualize the different phase relationships if the method described in the paper be used, rather than the ordinary method. For example, in a certain case, one hundred volts, making 45 deg. with the horizontal axis will be represented as $141\ j^{\frac{1}{2}}$, instead of $100 + j\,100$.

The question was brought up by Dr. Whitehead in regard to double-frequency quantities. Really, that does not come entirely within the scope of this paper. I would like to take that up in detail with Prof. Whitehead, but here I may say that personally I think that double frequency is an unnecessary complication. It was introduced by someone who was interested in it, and I think it leads into rather unscientific inconsistencies, and I do not think it has any importance.

John B. Whitehead: Perhaps I have used an unfortunate expression in the words "double frequency". Certainly I have not made myself understood by Mr. Diamant. I simply refer to the fact that it was not meant to include what is usually called the double-frequency quantity, which is treated by Mr. Diamant, at some length.

N. S. Diamant: In answering I may say that some persons start with vector quantities, and use these exclusively and suppress the use of instantaneous values. But the scientific definition of power is the one given in the paper involving instantaneous values, where the mean power is obtained by integrating or summing up the instantaneous power over a half cycle. This does not lead into the difficulties of changing the sign, and dropping out the imaginary portion of the product into which one is led when he uses vectors entirely. This vector definition of power leads into what we might consider a quaternion, that is, a quantity made up of scalar and vector components; but power itself is a kind of scalar quantity since it is fixed when its magnitude and sign—whether positive or negative—are given, and it requires no additional information as to its direction, as the true non-localized vectors of vector analysis do. The double-frequency idea is designed to get around this difficulty, and in a way gives physical explanation of it, but I think it is unnecessary, and a round-about step to take.

Presented at the Pacific Coast Convention of the American Institute of Electrical Engineers, Seattle, Wash., September 5, 1916.

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A DISTRIBUTION SYSTEM FOR DOMESTIC POWER SERVICE FROM COMMERCIAL AND ENGINEERING STANDPOINTS

BY CARL H. HOGE AND EDGAR R. PERRY

Abstract of Paper

The adoption of electric heating and cooking has begun to reach such large proportions that the average distribution system is unable to take care of the increased load. As the domestic power load in all probability will increase until every house is electrically equipped, this paper has endeavored to lay outa distribution system to take care of this class of business and to estimate the revenue to be derived from it. Units of load, consumption and revenue were taken from tests conducted in different parts of the city and applied to a definite section of the city thought to be representative, as it contained every class of house, with schools, churches, etc. In view of the results obtained, it would seem that this business would be profitable at a still lower rate, and that it would be advisable for the central station man to make provision for this increased load when rebuilding any lines in the future.

DOMESTIC power is so rapidly attaining large proportions in the central station business that present distributing systems and practises are quite inadequate, and it is daily becoming more imperative to revise our methods to include this class of service. By domestic power we mean all the electricity that is used in the home, and have classed it thus:

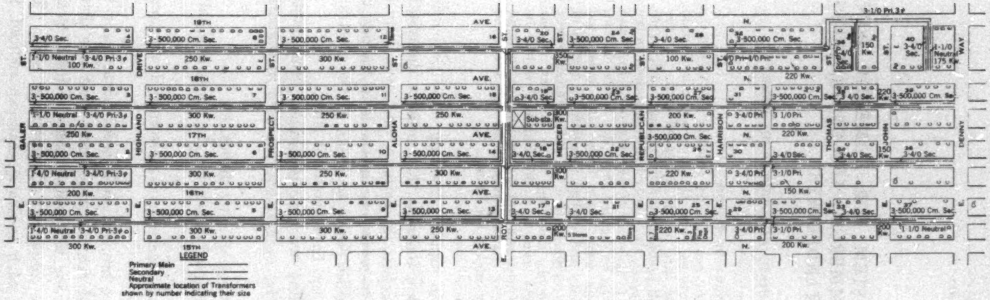
Lighting, including ironing, washing machines, small motors and appliances of all sorts, excepting those used in preparing meals.

Cooking, including toasters, chafing dishes, etc.

Heating, all current consumed in keeping the house at a habitable temperature.

Hot water heating for such water as is consumed in the household.

The past few years have brought such rapid advances in the perfection of cooking and heating appliances that our distribution systems are beginning to groan under the load, having been designed to provide amply for illumination only. The downward trend of rates, such as Seattle has experienced, has


GALER ST.
HIGHLAND DRIVE
PROSPECT ST.
ALOHA ST.
ROY ST.
MERCER ST.
REPUBLICAN ST.
HARRISON ST.
THOMAS ST.
JOHN ST.
DENNY WAY
19TH AVE. N.
18TH AVE. N.
17TH AVE. N.
16TH AVE. N.
15TH AVE. N.
Sub-sta.
LEGEND
Primary Main
Secondary
Neutral
Approximate location of Transformers shown by number indicating their size

MAP SHOWING HOUSES AND PROPOSED DISTRIBUTION SYSTEM.

TABLE I

CLASSIFICATION OF HOUSES

B = Large residence over 2 stories
C = Full two stories, medium size
D = Story and one-half, medium size
E = One story, medium size
F = One story, small size
St. = Store in a store building

Ch. = Church
Ap. = Apartment House, average about 20 apartments each
Apt. = One apartment in an apartment house
Sch. = School building of the Public School System
F.H. = Fire Apparatus Station

done much to popularize the use of electric current for all purposes, and the central station man is becoming more concerned about the return from this class of business. Hence, we have prepared herewith a preliminary analysis of the ultimate conditions in five, or ten, or twenty years, when every house will be electrically equipped with light, cooking, heat and water heating, and have designed such a distribution system as would be required, keeping in mind the commercial aspects of the situation.

In order to arrive at definite ends we have made numerous assumptions of conditions, which are based on the most advanced knowledge of the present time, and from these have projected our hypothesis. A definite section of one of Seattle's leading residence districts was selected and from a thorough canvass each house was assigned to a class representative of its size and electrical consumption, as shown on the accompanying map, the key for which is given in Table I.

This district is known as Capitol Hill and is very representative as it includes houses of every type, with schools, stores, etc., and might be used as a " unit " in estimating similar conditions for a city. We have also assumed that all construction must comply with the State Law and City Ordinances governing overhead lines, and that the rights of other public service companies must be observed, and further that all apparatus, wire and materials shall be such as are now considered as standard. Our assumptions also provide that no further houses are to be built in this district and that property now vacant will be utilized for park purposes, so as to require no electrical energy.

During the past two years, we have conducted a series of tests on cooking and heating loads, the results of which have been indicative but not conclusive. Certain constants and factors have been determined, however, upon which we can base our computations. These factors are fully defined in Table II.

For the lighting we have taken a group maximum demand factor of 25 per cent as indicated by a check of conditions in this district; cooking has a demand factor of about 19 per cent; heating will average 50 per cent, while hot water heating as used here is a full 100 per cent. It is well to remember that these factors will vary materially with the kind of people who use the service and their daily habits, hence conditions obtaining in Seattle may differ materially from those in other cities. In the cooking tests, fifteen ranges in different parts of the city were selected, and by means of recording meters the characteristics of the load were determined. The heating tests included fifteen consumers who used all types of heating apparatus. From these sources then the data of Table III were selected, being the units of load, consumption and revenue assigned to each class of house. The rates applying to this business are quoted in Table VI. Having chosen suitable units, they were applied to the district outlined and the totals for this district computed, as in Table IV.

TABLE II
DEFINITIONS

Connected Load = Sum of the rated loads

$$\text{Group Maximum Demand Factor} = \frac{\text{Maximum of the resultant curve combining all the individual max's.}}{\text{Connected load}}$$

$$\text{Individual Maximum Demand Factor} = \frac{\text{Individual max. demand}}{\text{Connected load}}$$

$$\text{Group Daily Load Factor} = \frac{\text{Total kw-hr. consumed per day}}{\text{Group max. demand} \times 24}$$

Peak Demand Factor = Per cent of the group maximum demand that occurs during the system peak between 5:30 p.m. and 6:30 p.m.

$$\text{Individual Daily Load Factor} = \frac{\text{Kw-hr. consumed per day}}{\text{Max. demand} \times 24}$$

Peak Max. Demand = Group max. demand × peak demand factor

$$\text{Diversity Factor} = \frac{\text{Arithmetical sum of all the individual maximums}}{\text{Maximum of the resultant curve combining all the individual maximums.}}$$

The term "group" is here used to indicate all the appliances of one class, such as "water heaters." or "cooking," that occur in the district under discussion.

Lt. = Lighting, etc.
Ck. = Cooking, etc.
Ht. = Heating
W.H. = Water Heating

In order to properly design a distribution system to take care of heavy loads of this kind, it is necessary first to combine them into units; second, to determine the connected load in each unit from which the unit maximum demand can be figured using the group maximum demand factor; and third, to design a feeder system to take care of the load. For example, we find that in

TABLE III.

UNIT OF LOAD, CONSUMPTION AND REVENUE

		Connected load in kw.				Kw-hr. per mo.				Dollars per mo.			
	No.	Lt.	Ck.	Ht.	W.H.	Lt.	Ck.	Ht.	W.H.	Lt.	Ck.	Ht.	W.H.
B	17	3	8	30	1.0	70	300	2130	720	3.00	6.00	16.0	3.50
C	321	2	6	20	0.8	30	224	1332	576	1.65	5.00	10.0	2.80
D	210	1.5	5	15	0.6	20	106	1000	432	1.10	3.00	7.5	2.10
E	57	1.0	5	5	0.5	13	94	667	360	.70	3.00	5.0	1.75
Apt.	145	1.0	5	5	0.5	25	166	667	360	1.40	4.00	5.0	1.75
Sch.	1	5.0	20	50	5.0	172	1000	13320	3600	5.00	20.00	100.0	17.50
Ch.	3	5.0	6	30	0.5	172	250	8000	360	5.00	5.00	60.0	1.75
St.	16	3.0	—	10	0.5	170	—	2670	360	5.10	—	20.0	1.75
F.H.	1	3.0	—	20	1.0	170	—	1332	720	5.10	—	10.0	3.50

TABLE IV.

TOTALS FOR DISTRICT

LOAD, CONSUMPTION AND REVENUE

	Connected load in kw.				Kw-hr. per month			
	Lt.	Ck.	Ht.	W.H.	Lt.	Ck.	Ht.	W.H.
B	51	136	510	17.0	1190	5100	36200	12240
C	642	1926	6420	256.8	9630	71904	428000	184896
D	315	1050	3150	126.0	4200	22260	210000	90720
E	57	285	285	28.5	741	5358	38000	20520
Apt.	145	725	725	72.5	3625	24070	96700	52200
Sch.	5	20	50	5.0	172	1000	13320	3600
Ch.	15	18	90	1.5	516	750	24000	1080
St.	48	—	160	8.0	2720	—	42700	5760
F.H.	3	—	20	1.0	170	—	1332	720
Total	1281	4160	11410	516.3	22964	130442	890252	371736

	Dollars per month				Dollars per year			
	Lt.	Ck.	Ht.	W.H.	Lt.	Ck.	Ht.	W.H.
B	51.00	102	272	59.50	612	1224	3264	714
C	529.65	1605	3210	898.80	6356	19260	38520	10786
D	231.00	630	1575	441.00	2772	7560	18900	5292
E	39.90	171	285	99.75	479	2052	3420	1197
Apt.	203.00	580	725	253.75	2436	6960	8700	3045
Sch.	5.00	20	100	17.50	60	240	1200	210
Ch.	15.00	15	180	5.25	180	180	2160	63
St.	81.60	—	320	28.00	979	—	3840	336
F.H.	5.10	—	10	3.50	61	—	120	42
Total	1161.25	3123	6677	1807.05	13935	37476	80124	21685

block No. 1 there are 14 class *C* houses and 12 class *D* houses having a connected load of 46 kw. in light, 460 kw. in heat, 144 kw. in cooking, and 18.4 kw. in hot water heating, a total of 668.4 kw. Using the group maximum demand factors as shown in Table V, we have 11.5 kw. in light, 27.8 kw. in cooking, 230 kw. in heat and 18.4 kw. in water heating, making a total of 287.7 kw. for the maximum demand of this unit. Proceeding similarly with blocks 5, 9 and 13, we find unit maximum demands of 310 kw., 273 kw. and 234 kw. respectively.

After covering the entire district in this manner, it seemed advisable to install a feeder from a centrally located substation for each 1000 kw. or thereabouts, which is the case in blocks 1, 5, 9 and 13. We find that in order to properly distribute 1000 kw. at 2300 volts, a three-phase, 4/0 feeder would be the most efficient, on account of initial cost, voltage regulation, carrying capacity of the wire and economy of space on the poles. We propose to maintain a constant voltage at the center of load on each feeder, and if necessary, to install transformers with variable taps to give the same voltage over the entire secondary. The load being essentially single phase will necessitate instal-

TABLE V.

LOAD CHARACTERISTICS AND REVENUE

	Conn. load kw.	Group max. dem. factor	Group daily load factor	Max. dem. on peak	Peak dem. factor	Diversity factor	Group max. dem.	Aver. daily load kw.
Lt.	1281	25.00%	10.0%	320.	100.0	1.0	320	32
Ck.	4160	19.34%	22.5%	804.	100.0	2.5	805	181
Ht.	11410	50.00%	21.7%	5705.	100.00	1.5	5705	1238
W.H.	516	100.00%	100. %	516.	100.00	1.0	516	516
Total	17367	38.6	29.4	7325.				1965

	Average kw-hr. per			Dollars per year	Av. rate per kw-hr.	Av. rate per kw-yr.
	Day	Month	Year			
Lt.	765	22964	275568	13935	5.06c	$43.50
Ck.	4348	130442	1563304	37476	2.40c	46.50
Ht.	29675	890252	10683024	80124	0.75c	14.00
W. H.	12391	371736	4460832	21685	0.48c	42.00
Total	47179	1415394	16984728	153220	0.902	10.90

ling single-phase regulators on each circuit at the substation. As all standard apparatus for domestic use is built for 110 volts to 120 volts, we will string a 1/0 neutral over the entire system, which will give 120 volts between this wire and any outside leg of the three-phase, 207-volt secondary bus, and will provide a ground for the transformers. The secondary bus will be a 500,000-cir. mil cable, except in cases where the load is concentrated at the transformer. We propose to install transformers either in single-phase units or in one three-phase unit as near as possible to the center of load in each block or group of blocks, depending upon the load. On the accompanying map we have shown the distribution as outlined above, including transformers.

TABLE VI.

RATES FOR DOMESTIC SERVICE

Lighting and Cooking:

Electricity for these two purposes is sold through one meter, at the following rates:

First 45 kw-hr. per month @ 5½ cents per kw-hr.
All over 45 kw-hr. per month @ 2 cents per kw-hr.
Minimum charge 50 cents per month.

Heating:

Rate: 1 cent per kw-hr. unrestricted, or ¾ cents per kw-hr. if used off peak. Minimum $12.00 per h.p. per year.
Peak hours are from 4:30 p.m. to 7:00 p.m. in winter and 5:30 p.m. to 7:00 p.m. in summer.
All service has been figured at ¾ cents per kw-hr.

Water Heating:

Rate: Flat charge of $3.50 per kilowatt-month.
Heater to run continuously.

In order to determine a reasonable cost for this system, we have assumed prices of material and transformers that were current prior to the present war prices and have arrived at a total figure of $111,400.00. This includes all local distribution outside of the substation, services and meters.

In Table V the revenue from the business as outlined has been computed, making a gross of $153,220.00 per year. The kilowatt-hours total up to 16,984,728 per year, and the average rate for all classes of service is 0.9 cents. The average return is $20.90 per kilowatt-year.

In concluding, we believe that the development of domestic power will necessitate the complete reconstruction of existing lines. New substations will have to be built for each 10,000 kw. of load and located approximately at the center of the district served. The heavy load in this service will require three-phase distribution, which will also take care of small power loads. We believe that domestic power can be developed into a profitable part of the central station business, and sold at a price that will be attractive to the consumer. The present rate schedules, which necessitate two meters and a flat cut-in for this business, are not satisfactory and a new basis for charge must be developed that will utilize a simple, inexpensive meter and can readily be understood by the layman. With increasing volume of business, the rates can be lowered materially below those quoted herein, and still yield an adequate return. It is up to the central stations to make an intensive campaign for domestic power service, for this is the solution of the problem of profitably serving residence business.

DISCUSSION ON "A DISTRIBUTION SYSTEM FOR DOMESTIC POWER SERVICE FROM COMMERCIAL AND ENGINEERING STANDPOINTS" (HOGE AND PERRY), SEATTLE, WASH., SEPT., 5, 1916.

D. F. Henderson: In Table III the paper gives the consumption per month for the heating installation, as 1332 kw-hr. I would like to ask the author how that figure is computed. Is it taken from actual experience? I have been heating my own residence this past winter electrically, and have installed a maximum demand very similar to his. I have a demand of 21 kw., but the kw-hr. consumption is almost ten times what is given in this figure. Of course our climate in Spokane is somewhat more severe than it is here, but it seems to me there should not be such a great difference in the kw-hr. consumption.

E. R. Perry: I think, Mr. Henderson, that that figure is sort of an average that we found around here with our climatic conditions. Of course you realize here that the people only use their heating equipment about six months out of the year.

D. F. Henderson: That is based on a six months' period?

E. R. Perry: It is an average for the twelve months; that is the total for the year divided by twelve months. You say that you have about ten times that much in a year?.

D. F. Henderson: Yes, during the severe winter months.

E. R. Perry: Per month you have about that much you say? If you add up the total amount of current you use during the year and divide it by twelve?

D. F. Henderson: It would reduce it very materially.

E. R. Perry: And the difference in temperature between Seattle and Spokane is very great.

J. B. Fisken: I believe that the idea is to run out single-phase feeders from the substation. That was our practise up to within the last year or two and then when times got hard and expenses were going up and income was going down, we skirmished around to find some way of serving the same load a cheaper way. We converted our single-phase feeders into three-phase feeders; our cables were six-conductor cables and formerly contained three single-phase feeders. We converted those into one three-phase feeder with a neutral wire, installing the single-phase regulators on each leg. Each leg was controlled by a single-pole automatic switch so that trouble on any of the three-phases did not affect the other two. We have found that worked out very satisfactorily and I would like to ask the author whether, in his figures as to costs, he figured on three single-phase feeders or one three-phase feeder with a neutral brought back?

The other point that occurred to me was whether or not the secondary was one interconnected system? Of course, in d-c. work, we find it is economical to connect the mains together everywhere, and it should be done the same way in a-c., work, but just how it is to be done, I don't know. There are two ways I have heard of, although I have had no practical experience and

I would like to ask for the practical experience from those who have had it. One is to introduce fuses between the secondary districts so that the trouble in one will take care of itself and not interfere with the others. And the other method is to introduce reactance so high that a short circuit on one section, which might blow the fuses in the transformer and stay on, would not over load the neighboring districts materially. Of course, they would be overloaded to some extent, but the voltage drop through the reactance would be such that the neighboring districts would be fully maintained and fairly satisfactory service rendered until the trouble could be removed.

E. R. Perry: I believe, Mr. Fisken, that your idea, or the system which you describe, the three-phase system with a return neutral, is the one we have here. We have in mind a single regulator on each phase; it will not be necessary in this case to have a single-pole switch because there will be three-phase distribution down each street or alley, as it were. We will not take the single phase off the three phase at any place, or run a separate feeder line with bus line, single phase. All bus lines will be three phase and the secondaries will be three phase, and will extend over districts of approximately one block, or one unit as we have determined here; in some cases a little over a block, depending on the load. There is a transformer for each block, each transformer with its own secondary circuit about one block long; the secondaries not inter-connected.

M. T. Crawford: The plan of the distribution system outlined in this paper is most economical in first cost, but it has the disadvantage of not being easily installed from time to time as business grows. The complete domestic electrical installation, anticipated here, will only be gained one unit at a time, and will be many years in coming. The trend of distribution systems in the better city districts, is toward underground construction. A 4000-volt three-phase four-wire distribution system using 2200-volt standard transformers between the outside wires and the neutral would permit the use of about one third of the primary copper specified in this paper. A small transformer vault installed adjacent to the basement wall of each residence, would permit service wires of approximately No. 12 copper, which would be duplex cable and in an iron pipe. This would take 2200-volt power direct to the consumer's house, and make the short service leads between the main switch and this transformer vault, the only heavy copper necessary. This system would cost more, principally because of the larger transformer capacity necessary, it being impossible to utilize the diversity factor of the various consumers' installations. In practise, some way of overcoming this difficulty could be devised, as by feeding several houses close together from one transformer vault, or putting in secondary tie connections. One consumer could be taken at any time on any part of the system, and this method of installation could be put in for that consumer; and as more are obtained the same scheme followed until eventually, when the complete electrification mentioned is obtained the mains could be put under ground, if desirable, at a reasonably small additional cost; that is, little of the existing equipment would have to be changed. That is simply my idea of what would be the best service, even though at a higher total cost, and it would certainly meet with more favor from the people. The size of copper on the lines and in the service wires, as mentioned in this paper, would make such heavy wires as to detract somewhat from the appearance of a strictly first class residence district.

F. D. Weber: The author has a demand factor of about 19 per cent for heating. I would like to ask if any demand factor has been computed for residences, apartments and the various classes of cooking. In Portland we have been very much interested in knowing what size feeders should be supplied for group cooking, such as apartment houses.

E. R. Perry: We have no information upon that, Mr. Weber.

C. R. Collins: It is rather difficult to appreciate the magnitude of this proposed heating load. You will notice in Table I, nearly every block shows a load of 250 or 300 kw. The present density of load in the down town district of Seattle averages 150 kw. per block. The proposed distribution system for residence districts must take care of at least twice the kw. load per block that we now have in our most densely settled business district. The author calls our attention to the fact that we will have difficulty with our distribution system. It is also interesting to consider the increased demand on our generating equipment. I have taken the figures given in this paper and secured the average kw. requirement per customer, which is about eight kw. In Seattle we have probably 50,000 consumers such as would come under the description given in Table I, 400,000 kw. would therefore be required to supply our residence districts. At the present time it requires not more than 25,000 kw. to supply the residence load.

This means increasing our present residence load sixteen times. It is also interesting to note that when we do increase our present load by that amount, that load is going to determine our peak and all other loads will be incidental.

In Table V, in the lower right-hand corner are given the returns for a kw-yr. You will note the return for the heating, figured at $\frac{3}{4}$ of a cent per kw-hr., is $14 per kw-yr., and you will also note that the kw-hr. consumption for heating is approximately 65 per cent of the total kw-hr. consumption given. The only chance of electric heating becoming commercially possible is that it will be possible to reduce very materially the cost per kw-yr. of generating power. $14.00 per kw-yr. is very much below the present cost.

W. D. Peaslee: I am very glad to see brought out, the open advocation of a one-meter rate for lighting, cooking and heating. To my mind that point strikes the key of the whole situation. The idea of electrical engineers being held down at the present date, in the present state of our art to having to insist that every time a man wants to do something, he has a different rate put on his load, is something of a joke. In the case of the little town of Corvallis, I have some electric light and cooking appliances in the house for which I have a separate meter; if I put in a hot water heater, I have another meter for that or a flat rate, which really gives me three separate services in that house, with the attendant overhead expenses and clerical expense for the company on each of those billings.

Now, there are two solutions of the rate as given here. Either have a very high minimum and a low energy rate, which the public will immediately object to; or take the rate as given in the paper, the first 45 kw-hr. per month at 5½ cents, a minimum charge at 50 cents per month and the rest of it at two cents per kw-hr. That first 45 kw-hr. is going to make the man's bill big enough if he uses any electric heating and cooking at all in the house, so that the company will be protected. They will get their cost of testing meters and their cost of billing and all those things that go into the beautiful theoretical rates that are worked up. At the same time the customer will have one meter in his house and he can subtract the previous month's reading from the present reading and figure out for himself what his bill is coming to; but you take the class rates of power companies today, and he is a better man than some engineers if he can do it. I think that one of the biggest factors we are going to find in the development of heating and lighting load for electrical power, is to have a rate that protects the power company by having either a high enough minimum to take care of these incidental expenses, or have the first block of energy at a sufficiently high rate so that any ordinary consumer is going to get a big enough bill to come up to the point necessary, and then a very low energy charge for the rest of it.

I know of one location in Oregon where it worked out. A man is permitted to take on a load for heating, lighting, cooking and hot water and anything less than a one-horse power motor at any time of the day or night at $5 a month minimum, and one cent per kilowatt hour energy charge. That is a little drastic and it may be a $5 minimum is wrong, but personally I believe that some form of rate of that kind for the high minimum and low energy consumption is going to build up the load until our heating and lighting load will not be as it is now, but may ultimately approach the figure given in this paper of 200 or 300 kw. per block in first-class residence districts. I think that, the only way the power companies will be able to build up is to get a rate of that kind.

F. D. Weber: Near the end of the paper I note the author computes his gross income per year. I wonder if anybody has investigated the statistics and found out the amount of money an average family both poor and rich can spend per month for lighting, heating and power. At one time I saw a statement covering 20 years in the lighting industry, showing that the annual monthly bill has been nearly a constant amount. I think it would be well to investigate on the customer's side and see how much money they will actually spend. If they are using gas, they spend so much money; if they change to electricity they will spend a certain percentage more for the added convenience.

E. R. Perry: I think that in selling electricity we sometimes lose sight of the fact that we are really selling a commodity just like sugar in the open market, and we have to compete with all the other forms of energy that people use to reach the same end that we want to sell our electricity for; and for that reason it is well to think of how much a man in moderate circumstances can afford to pay for the electric energy that we want to give him. Now we might imagine a family of three or four living in a house of six or seven rooms, and if he heats with hot water, his heating bill is going to be somewhere about $70 or $75 a year, if he is economical, and his cooking bill for gas will be something like $35 or $40 a year,—cooking and hot water, possibly. His hot water service, however, will be intermittent and he will only light up the gas heater when he wants it, and he will not have hot water all the time. That I think will total up somewhere in the neighborhood of $140 or $150, that he is paying per year for lighting, cooking, heating, and hot water from the different forms of energy that he gets now.

Suppose he purchases electric energy according to the way the rates are now. He would pay somewhere around $200 on an average for the same service; it is a little bit difficult at the present time to make people see the $50 additional value in the electric service. Possibly they do not realize they will only have to pay $50 a year more for an entire electric installation. This is an average case. Of course, some cases are going to run higher and some lower. I do not think the people at the present time are educated up to that point where they would want the electric service with the additional value in it and the additional convenience of it. With the competition we have in all other forms of energy, it is very hard to sell electricity at the present rates, and with the handicap of installations already put in for the other types of service. Now, if a man is just building a house and he could get all these things and it would cost him only $50 a year more, he would put them in without hesitation, I believe. But where he has already tied his money up in apparatus to use coal, gas and so forth, it is pretty hard to make him junk all that and put in the new electric service.

The point about the metering of the service is one which I feel is very important in the sale of energy for domestic use. Selling electricity as we do now, with two or three or four meters, is just like selling sugar by the quart to a man for putting up fruit, and by the pound for making candy. He can not see it, and the quicker the central station gets to the point where they can sell a man so much electricity for a certain price and don't care what he uses it for and have it taken care of in the rates, that much quicker are we going to get simplicity in accounting, metering and in the whole business, even down to selling it to the customer. The quicker people understand about our electric game, just that much quicker are we going to make strides in it.

E. G. Robinson: I have been considering the one-meter rate a good deal and I have come to this conclusion: That if you make your heating load 220 volts instead of putting in a three-wire meter,—if we put a straight 220-volt meter in, and then tap our lighting on the neutral,—run in three wires, the two 220 volts and the neutral, then we can tap around the two wires with the neutral and fix it so that all our electrical appliances for heating would be 220-volt. Then for our lighting, simply tap the series circuit of the meter, and that will make our lighting current register just twice as fast as our heating current. So, if we were making a heating rate at three cents for a certain block, while that was being used, we should be getting six cents on all our 110-volt socket appliances and we would be getting three cents out of the straight 220-volt current, because the current flowing through the meter would register at 220, while only being used at 110. I simplified our system that way and used but one meter for the man who takes power. We tap a neutral around the polyphase meter and let him use current at 110 volts, with all appliances forge blowers and such as that. I am quite in sympathy with simplifying the rate, and I believe that any man who is figuring on doing this should simplify it as much as possible, because the average layman thinks that blocks of kilowatts, amperes and so forth, are intended and designed to befuddle him as to what he is buying. I have not yet tried out the 110-220-volt scheme on heating, only on power, but I hope to do it; and I believe it gives a complete solution of the problem of one meter with two rates.

By the way, I would like to ask that if in this distributing system where you are going to use one neutral, would that not necessitate the hooking up of your transformer star instead of to delta? It has been my experience that 90 per cent of our transformers for distribution are delta connected. Now if you wire them up star and one goes out, that puts that entire system out. I would like to know how you take care of that?

E. R. Perry: It has that disadvantage, and a protective device would have to be used.

E. G. Robinson: In thinking that over we, of course, think you are going to have delta transformers.

E. R. Perry: It would have to be star to utilize the neutral. Nearly all our apparatus is 110 volts and 220 volts, and it would be necessary to have both voltages in each house. In order to accommodate present wiring we would have to have the three-wire circuit, as it is called, in each house.

L. T. Merwin: I would like to ask the author whether the decision on using four-wire three-phase as against a three-wire three-phase connection is made on the basis of regulation for commercial economy.

E. R. Perry: I think, Mr. Merwin, that we provided a four-wire delta connection in order to accommodate the present type of household utensils which require 110-220 volts. We have a star system with three-phase 207 volts on the outside; that would give us 120 volts to the neutral.

H. W. Buck: The author spoke a few minutes ago about the average householder not being educated up to the use of certain applications of electric power. I should like to ask what the experience has been on the Pacific coast with the average householder in the use of household electrical appliances. Is it necessary to have an electrical engineer in each house to satisfactorily operate these various devices, or do the public as a whole take hold of them intelligently and operate them efficiently? It does not take much intelligence to turn on an electric lamp, but it takes considerably more technical knowledge to operate an electric washing machine, electric range and some of the other devices that are now used.

E. R. Perry: I think that the people who have taken out electrical devices have learned to use them very intelligently, and the amount of trouble developing with the different appliances is very small. Once people get interested in these things, and really appreciate their value, they seem to develop an undue amount of electrical wisdom. I think that if we can only get to the people and get them interested, it would be easy enough to educate them.

The next step in that direction is the electrical equipment of all of the home economic departments of the various schools and colleges in the country, and the training of the girls of the younger generation to know and use intelligently all forms of electrical appliances and apparatus, and to make their own minor repairs. I believe that the coming generation of girls are going to know a great deal more about electric household utensils than the present generation of housewives do. It is only through educating the younger people that we are going to successfully solve this problem. The older people do not learn quite so readily, but those who do, as far as experience around here is concerned, have been able to take up these things and learn to use them very quickly.

S. M. Kennedy: The question which you have asked in reference to the manner in which the purchasers use apparatus is one that is very easy to answer, if you have had much to do with the handling of such appliances. What are called lamp socket appliances are very readily handled and it does not need any engineer and requires very few demonstrations to teach the housewife to readily use any such appliances. Even the washing machine, which is a little more complicated to operate, practically runs itself with a turn of the switch. However, when you get into the broader field of cooking—I mean major cooking,—we find that the average housewife in Southern California, while she is anxious to learn, does not pick up quite as readily the methods of handling the electric range and of substituting it for whatever method of cooking she has been used to, heretofore. In the kitchen the average housewife is a little bit sensitive; she has a pride in her work; and she does not like anyone to come in to show her how to do her work. That kind of education must be done very diplomatically,—the average engineer cannot do it at all. We find that it pays to have tactful, experienced and good looking lady-demonstrators, who can follow up the range installations and go from place to place, and find out first, whether the lady who is doing the cooking thoroughly understands the method of operation and whether she is getting the best that is possible out of the range and for the least amount of energy put into it. If she finds that things are going all right, the demonstrator tells her so. If, however, she finds that they are not going all right, that in some parts there is too much heat turned on when it is not required, and not enough in other parts of the stove, she must be tactful and explain just how the operation should be done in order to get the greatest efficiency. The demonstrator must be educated and trained for that particular kind of work, so that she not only understands the stove and the operation of the stove, but she must also understand human nature.

J. B. Fisken: The average farmer of eastern Washington is notorious for not taking care of his appliances,—I do not mean electrical appliances, I mean his agricultural appliances,—and it might be interesting to learn whether the electrical appliances, cooking and so forth, have caused much trouble. Mr. Chrysler handles four country towns and a number of farmers and he could tell us what his experience has been.

W. L. Chrysler: We find less trouble with farmers taking care of their electric equipment than the consumers in town. These farms are run on a large scale by combined harvester tractor and modern machinery, which makes the farmer a mechanic for he has to operate and keep up his own equipment. We have a few farmers on our lines who have quite complete electric-equipment. They make their own minor repairs, while the consumer in town will call the fix-light department.

J. R. King: The point I want to bring out is the fact that it is becoming more and more apparent in the development of electric house heating, not cooking or hot water heating, but to heating the home, that the ideas of the electrical engineer, more especially of the man who has charge of the operation and the control of the delivery of power, have got to be changed. That is, he has got to recognize new conditions coming in. For instance, you will note in Table V, that there is a group maximum demand, 320 kw. for light, 805 for cooking, 5705 for heating, and 516 for water heating. Referring to one of the other tables the rate is one cent per kw. hour unrestricted or $\frac{3}{4}$ cents per kw. hour if used off peak. It appears to me from this paper that the factor which produces the peak is no longer lighting, which comes on about half past four to seven o'clock. Power is a more or less off-peak product and cooking can be considered so to a certain extent. All the efforts have been made to take on this house heating rate under the same assumption and under the same condition, that the consumer will not use it during what is called peak. Now, the great preponderance of energy is used for heating and this demand would indicate that the time of the peak has shifted. Therefore, this paper would point out that in order to estimate in the future, demands for domestic service in residence districts, it is necessary to consider primarily what demand will be required for heating; and the lighting, cooking and hot water heating would be incidental to that. In other words, the determining factor is no longer lighting, but it is heating. In the Institute meetings and in the National Electric Light Association meetings and in other meetings, discussion on that has raged up and down and the argument that heating was a by-product has been advanced and contradicted. It appears to me, it will be necessary to figure very carefully in the future. What is the use of keeping off the peak, if the heating itself establishes that peak? If we keep the heating off the peak, it will not occur in the afternoon any more than it will occur at any other time during the day. Furthermore, what are you going to do on a cold winter day when the customer comes home and insists on having his heat? If he cannot have it, he comes right back and asks why he is not entitled to have it? Those are points that I think must be considered in planning the installation of any house heating. They are points that have arisen in connection with the sale of energy in Seattle. They are points that will be raised as long as house heating is promoted, whether or not the peak be shifted to another time of the day, and another class of energy other than lighting be responsible for it.

H. J. Gille: In the first place, this heating rate was filed with the Public Service Commission of this state as an experimental rate,—simply a try-out proposition. Second, the peak hours are the lighting-peak hours, which control at this time the distribution peak. It seems to me that in any discussion of the question of laying out a prospective distribution system to take care of heating and other appliances in residences, it should be important to know whether you are talking of a station peak or a distribution peak. The residence peak as we know, comes at a different time from the power peak, and the power peak at a different time from the commercial lighting peak, but all of the resultant peaks establish a certain peak on the station or a generation peak. By developing the electric heating, of course, the generating station peak would probably be transferred from the point where it is now, to some other part of the day.

C. R. Collins: We have conducted tests in connection with electric heating and one of our conclusions is that the electric heating peak may come at any hour in the day; sometimes it may be in the morning, sometimes in the afternoon and very frequently you will have a load almost as large as the peak about six or 6:30 p. m. So this peak cannot be considered as some other not coming on the system peak, which occurs about 6:00 p. m.

Robert Howes: In the early days the load on any separate feeder was small and scattered over considerable territory and it seemed to be necessary to use the low voltage of 110 or 220. With the growth of business and the growth in power consumption by each residence, such as is contemplated in this paper, the question raised by Mr. Crawford of placing individual transformers at the residence and omitting the secondary distribution system, may become one of material importance. In the development of power plants, in this district, at least, after you have reached a capacity of forty or fifty thousand kilowatts, the cost of generating power and bringing it to the central substation is not varied so very greatly, although it is to some extent, by additional capacity. You begin to reach a point where the cost of operation per kilowatt hour and the investment cost per kilowatt of development, does not vary by a very wide margin, although it will to some extent. It would seem it might be a decided advantage in such a case as described in this paper, to omit the secondary mains and simply use a high-potential distribution with transformers at each house or for two or three houses grouped together, using low voltage only for the houses. That would reduce the copper requirements and cost of good regulation. We cannot expect to obtain a great deal of reduction in initial cost per kilowatt after we reach a certain power plant capacity, but with additional capacity there is room for considerable improvement in the distribution systems and that seems the most promising field to look for reduction of cost per kw. hour in operating the system. It at least appears possible that with the demand per residence increased to such extent as here contemplated, there may be room to reduce the meter installation and attendance per kilowatt hour of consumption, and substitute small transformers at the point of use; distributing to advantage both in simplicity and in cost of investment and operation per kilowatt hour sold.

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SOME FEATURES OF DOMESTIC ELECTRIC COOKING AND HEATING

BY H. B. PEIRCE

ABSTRACT OF PAPER

Although electric cooking and heating has always been considered possible, it has only recently become popular; hence the engineer is found unprepared with information on the characteristics of the load.

From tests made on a number of domestic cooking and heating installations, it would appear that electric cooking has a better load factor than a lighting load and that this load factor improves as the number of ranges increases.

The errors incident to these tests are discussed.

The demand factors on being plotted against number of ranges appear to follow a logarithmic curve which may be accounted for by the fact that a modification of the law of probability would no doubt determine the probable coincident demand of a number of ranges and that this law is a logarithmic function.

Suggestions are made for the checking of these results by others.

In the heating field, the effect of water heaters superimposed on range loads is discussed in relation to their effect on the central station loads and income.

SINCE the use of electrical energy first developed, the possibility of successful heating or cooking by heat, generated electrically, has never been questioned; the problem has always been—can it be done at a profit to the central station, with energy sold at a price low enough to put electricity in competition with other fuel?

Today we find a sudden stampede for this ideal fuel, but we find the electrical engineer unprepared to solve the problems of heating and cooking electrically.

It will be the province of this paper to show what may be expected by a central station after there has been developed a load of ranges and water heaters, and along what lines engineering assistance is needed to solve certain knotty problems connected with this phase of the industry.

First, to consider the effect on the central station of a cooking and heating load. It would be natural to expect that a cooking load would have a load factor considerably lower than the lighting load in the same community. This we find is not the case and it further appears that there is a greater increase in load factor in a cooking load by reason of an increase in number of consumers served, than would be gained in a lighting load by such an increase of consumers.

These deductions are the result of a number of tests made on actual water heater and range installations in homes using electrical energy for cooking and water heating.

The tests consisted of installing recording ammeters on the various cooking installations and reading the charts taken therefrom to the nearest five-minute interval; these readings were then assembled and the total load for any day at any hour determined.

A number of assumptions were of necessity made in securing these composite loads.

First, it was assumed that the clocks of the various meters were synchronous. This is in error for two reasons; (a) the charts were not all taken on the same calendar day but were taken at different seasons for different ranges and superimposed according to the day of the week on which the readings were taken; (b) the clocks were not absolutely accurate either as to time of day or as to speed.

Second, the readings were taken on a five-minute interval; this meant that the reading for the interval had to be integrated by inspection, which was, of course, is difficult to do with much accuracy, particularly in view of the fact that the swing of the needle on these instruments was considerable.

The first opportunity for error would appear to have more weight than it proved to exhibit in practise, since a set of charts for a week, taken at one time of the year, have a strong resemblance to similar charts taken during a week at another season. In other words, in the community observed, the habits of the public as it concerns the preparation of meals, appears to be uniform at different seasons of the year. The opportunity to run into error by inaccuracy of the clocks is so slight as to be incommensurable with the accuracy of the results which at best are only approximate.

Curves shown in Figs. 1, 2, 3, 4, 5, 6, and 7, exhibit the daily load of 42 ranges of assorted manufacture and varying capacity from 2.5 to over 6 kw. As the coincident maximum demand of these ranges can be obtained from the curve, and as

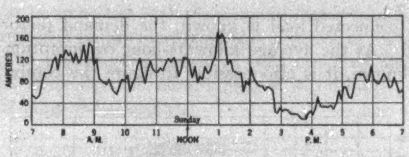

FIG. 1—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—Connected load 155.4 kw.—maximum demand 20.07 kw., voltage 116

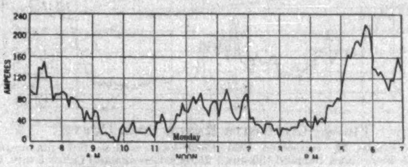

FIG. 2—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—connected load 115.4 kw.—maximum demand 27.75 kw.—voltage 116

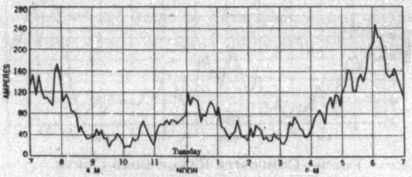

FIG. 3—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—connected load 115.4 kw.—maximum demand 28.65 kw.—voltage 116

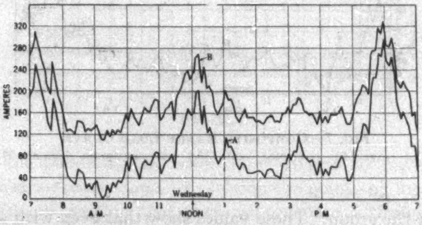

FIG. 4—COMPOSITE RANGE AND WATER HEATER LOAD, CURVE "B"

Number of ranges 42—number of water heaters 21—connected load ranges 155.4 kw.—connected load water heaters 12.18 kw.—maximum demand 37.47 kw.

the total connected load is known, the demand factor can be computed. As the average kilowatt-hour consumption of each range is known, it is also possible to figure the combined load

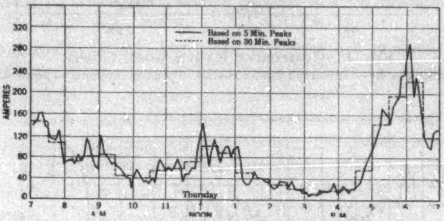

FIG. 5—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—connected load 155.4 kw.—voltage 116—maximum demand (5 min.) 33.75 kw.— max. demand (30 min.) 25.63 kw.— demand factor 5 min. peak 4.6— demand factor 30 min. peak 6.1— demand factor 30 min. peak (Wed.) 5.5

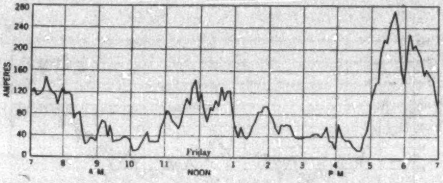

FIG. 6—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—connected load 155.4 kw.—maximum demand 31.43 kw.— voltage 116.

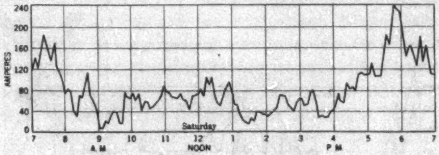

FIG. 7—COMPOSITE RANGE LOAD CURVE

Number of ranges 42—connected load 155.4 kw.—maximum demand 27.96 kw.— voltage 116.

factor of the group. These values show that even with as small a group as 42 ranges, the demand factor is 4.5; with 25 ranges, it has been found never to be less than 3.5.

It might be expected that the demand factor would increase as the number of ranges increases; this is shown in Fig. 8, where a number of groups of ranges have been observed for demand factor, and these demand factors plotted as ordinates with the number of ranges as abscissas.

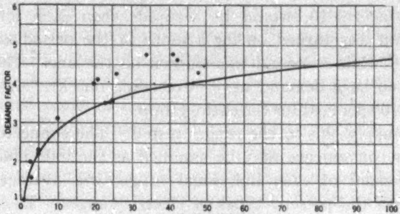

FIG. 8.

The result is a shot-gun diagram which interests us not so much in its upper limits as in its lower limits; that is, the worst condition which we are liable to experience in any given installation is that for which we must make provision. The curves

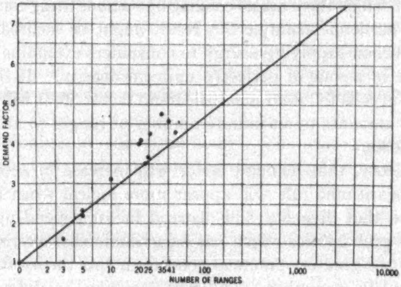

FIG. 9.

through the points on the lower limits appear to have logarithmic characteristics and by plotting the points on logarithm paper (Fig. 9) we find that they approximate a straight line, that is, they follow roughly a logarithmic curve.

Such a curve would have infinity as its upper limit and this we know is impossible, as the demand factor can never exceed the reciprocal of the average individual load factor.

It is possible that this last statement requires a word of explanation as it is not self-evident.

Consider ten installations, each with a demand of one kw., and an individual load factor of 10 per cent. The greatest demand factor, 10, would be secured when each individual installation was turned on for a tenth of the period and then turned off while a second was thrown on the line. The result would then be a demand never exceeding one kw. and a load factor of 100 per cent for the entire group.

Let us apply this to the ranges tested. The connected load, which for convenience may be assumed as the individual maximum demand of each individual range, will average about five kw. on the present types of electric ranges. These same ranges will each average a consumption of about 100 kw-hr. per month; that is, the individual installation will have a load factor of about 2.8 per cent. The reciprocal of 2.8 per cent, or 36, is then the maximum limit of the demand factor on ranges of this type. To reach this value it would be necessary for the combined load factor to be 100 per cent, which is of course impossible under present conditions as there are hours during the day in which there are no cooking operations being conducted.

As an academic example this result might be secured from a central station supplying energy to consumers extending around the globe in a zone of perfectly uniform density. If the logarithmic curve is followed out to demand factor 36, it will be seen that this amounts to an infinite number of ranges to all intents and purposes.

The theory, that demand factor will increase in accordance with a logarithmic rule will appear more logical when it is remembered that diversity and demand factor depend upon the theory of probabilities which has logarithmic characteristics.

To get the greatest practical good from this theory it should be checked in a number of different localities by different observers and the results compared; then, from the results, a rule adopted that would permit the probably coincident demand of a number of ranges to be more accurately predicted than is possible at the present time. These results should be of sufficient accuracy to enable the various electrical rules to be based upon them, so that it would not be required that excessive feed cables be provided for the care of apartment houses equipped with electric ranges, and so that the proper sizes of feeders and transformers for serving a load of ranges would be better computed by distributing engineers.

It will be noted that the demand factors have been figured in the computations so far made on the basis of a five-minute peak. For practical purposes such a peak is unnecessarily brief so that the effect of a 30-minute peak has been indicated on Fig. 5 by a dotted line which represents the results of measuring the demand by means of a demand meter of the type that integrates a load over a series of definite half hour periods.

Integrated peaks of half-hour duration will, of course, make the demand factor greater. This should be borne in mind in comparing charts taken in different cities.

In making comparisons, there should also be noted the class of people by whom the ranges are used. Those referred to in this paper are representative of all the classes that will eventually do their cooking electrically. They include families with incomes of less than $100 per month and homes in which the bill for current is a minor consideration. The apartment house dweller is, however, not as well represented as he should be. To show the effect of such consumers in helping to improve load factor, the demand factor of the ranges of one of the apartment houses in Salt Lake City is shown in Fig. 8. This demand factor, it will be seen is far in excesss of those secured from ranges installed in homes in Spokane, the city in which the individual tests were made. At first, this does not seem logical, as one would think that the dwellers in the same apartment house would come from the same walk in like and would be likely to do their cooking at the same hours. The answer probably is that they do less regular cooking than do the families in their own homes.

Another point that should be commented upon before leaving the subject of electric ranges is the average monthly consumption of the individual ranges in kilowatt-hours. This has been referred to above as being about 100 kw-hr. It is true that the value, 100 kw-hr., represents approximately the average condition, but to say that this is the probable consumption of any particular electric range, is quite another thing; the truth of the matter is that the consumption seems to vary between the limits of 50 and 250 kw-hr. while in exceptional cases the energy consumption of a range used by a farmer has been known to exceed 400 kw-hr. during a single month. This condition appears generally during the season of harvest when there is a large number of hands to feed. Attempts have been made to predict the consumption of a range by the size of the family by whom it is used; this the writer believes to be unsatisfactory as there are wide variations in habits between families of equal size.

It will be noted that for the ranges observed the daily peak occurs very nearly at 6 p. m. In other words, it will coincide closely with the lighting peak. This is unfortunate, but when it is remembered that with a fair number of ranges in use, the demand factor will probably be 8, the feasibility of making this business profitable with a low rate per kilowatt-hour becomes clearer.

For instance, if we assume a monthly consumption of 100 kw-hr. per range, an average individual demand of 5 kw. and a demand factor of 8, we get the following results with a rate of 3 cents per kw-hr. for energy:

Revenue per range per year	$36.00
" " kw-year of range demand	7.20
" " " " " station demand	57.60

So far this paper has dealt only with the electric range; the next point to be considered will be the heating of water for the home.

A supply of hot water is essential to the satisfactory use of the electric range; that this can, in many instances, be accomplished electrically, is not questioned. The problem is, how it shall be done.

To compete with coal, wood and gas, for hot water heating, electricity must be supplied at a very low rate. This can only be done by securing a high load factor for the service; by taking the supply from valley hours; or, by limiting the use of the heater to those hours when the range is not in use.

A high load factor can be secured for this service by installing the heaters on flat rate and assuming that they will be used continuously; this has the disadvantage of superimposing their load on the existing peak. The revenue they return must then be sufficient to yield enough per kw-year to pay for all the fixed charges depending upon maximum demand at peak.

The disadvantage of limiting the use of water heaters to the valley period of the system load is that a very large amount of hot water must be stored, as in most instances the valley hours are not of very long duration and occur at a time when there is no need for hot water. The result is that if the hot water supply is depleted during the day, there is no alternative for the consumer than to wait until the next day for more hot water. A further disadvantage is the expense of an installation to supply such a system. Time switch, large capacity heater, and large, well-insulated storage tank, all will be found to amount to a considerable sum.

The third method of limiting the use of the heater to the hours when the range is not in use, has some of the advantages of both systems with less of their disadvantages; it can be controlled by a double throw switch or by a special rotary snap switch now on the market for that purpose. The diagram of wiring for such an installation is shown in Fig. 10. The effect of such a water-heater load when superimposed on a load of ranges is shown in Fig. 4.

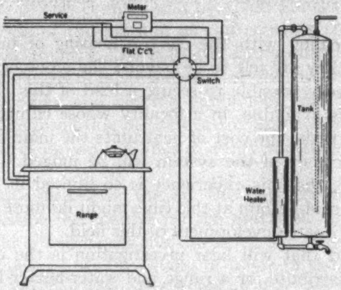

Fig. 10—Wiring Diagram for Electric Range and Water Heater Controlled by Special Switch

It will be seen from the curves on this figure that a load of 42 ranges gave a peak of 33.41 kw. when operated without water heaters, (Curve *A*). When 21 of the ranges were equipped with 600-watt water heaters on double throw switches, the peak was only increased to 37.47 kw. (Curve *B*).

A common rate for a 600-watt water heater operated in this fashion is $2.00 per month and if the ranges use an average of 100 kw-hrs. each per month the rate for energy being 3 cents per kw-hr. they would return a revenue of $36.00 per year per range or a total revenue of $1512.00 for the 42 ranges. These ranges show a demand of 33.41 kw. which means a revenue of $45.00 per kw-year when operated without water heaters.

If 21 water heaters pay $24.00 each per year, we would get an additional revenue of $504.00, or a total of $2016.00 from the ranges and water heaters combined. The demand is now raised to 37.47 kw. which gives a return of $53.70 per kw-year. It is conceivable that the addition of such a water-heating load might make an otherwise unprofitable installation of ranges, profitable.

Regarding the size of heater required for this purpose, there are few accurate data which can be offered. The 600-watt size appears to be the smallest that will work satisfactorily while it is seldom that a heater larger than 1.5 kw. is required. The number of people in the family, their habits, the size of the storage tank, the system of hot water distribution, all affect the results.

Problems dealing with the electric heating of buildings are so large that they are felt to be beyond the scope of this paper. It is undoubtedly possible to secure a load of this nature when cheap power is available, in a locality whose climate is not so rigorous as to make the cost of heat units the main criterion by which the efficiency of the system will be judged. The writer feels, however, that his experience is so limited in this regard that anything said by him at this time might do more harm than good to the ultimate development of this field.

Another field that will bear investigation is the question of how best to distribute for a range and water-heater load. The use of individual transformers for each range with no connection between the secondary lines is objectionable by reason of the high cost of installation. The use of safety devices between transformer secondaries for providing safety to adjacent transformers connected in multiple may make it possible to secure greater benefit from the large diversity that undoubtedly does occur between different groups of these appliances.

The question as to how the electrical engineers of today can best promote the development of electric heating and cooking and whether there is any phase of this subject that has been neglected by the Institute to the detriment of the electrical heating and cooking field and to the standing of the profession of electrical engineering is worthy of our attention in closing.

The electrical cooking of food does not appeal to the average engineer as worthy of his august attention, as it smacks too much of the work of the humble house maid. The big problems of large transformers and high-tension transmission appear far more important.

Is this position well taken? Is not the service of society the main object that should stimulate the engineering profession and is there any problem more worthy of the attention of the engineer than the problem of supplying food to the citizens of the community? Certainly this is a problem far more important than the problem of supplying the luxury of light.

The humble work of heating water is certainly as vital to the advance of the community as any that may, on the surface, appear more poetic by reason of the handling in one unit of a large capacity of power. The cake of soap has been considered an index of the progress of civilization, but of what little use is the soap without hot water to use it with.

The standards of the Institute have been looked upon by both the engineers of this country and by those abroad as indicative of the progress of the art and as representing the formulated practise of the country. Be it to our shame that there is in the rules of standardization no mention of the proper installation of electric cooking and heating appliances, and but one brief mention of the insulation of the heating and cooking appliances that are now in use on the lines of every central station in this country.

In the early history of the art the engineer with mistaken ideas of dictating the possible for the practical, developed heating and cooking appliances that impeded the growth of the use of electrical energy for the saving of labor in the home. Be it to the credit of a few men of wide vision that this is not the case today.

DISCUSSION ON "SOME FEATURES OF DOMESTIC ELECTRIC COOKING AND HEATING" (PEIRCE), SEATTLE, WASH., SEPT. 5, 1916.

J. B. Fisken: I want particularly to call attention to the paragraph in which the author refers to the manner of heating buildings. It is true that electrical heating of buildings may be practicable in one community and not in another. In our community, where we have a temperature varying from, perhaps, twenty degrees below zero in winter to one hundred above in summer, it would require a very much larger installation to furnish heat for buildings than it would possibly in Seattle, where the temperature variations are not so great.

C. E. Magnusson: It is essential, in order to secure a low price for electric energy, that we have a good power factor and a good load factor, and that there be taken into consideration a seasonal load factor as well as a daily load factor. If the heating of buildings entirely by electricity is to be undertaken, it means that for a short period of the year there would be a tremendous peak, and the rest of the year the installation would stand idle. To install a system for supplying electric energy for heating purposes which would be adequate for two months of the year when the demand would be greatest, and during that time be obliged to supply several times as much power as in the other ten months, when the demand would be very low, seems to me to be out of the question. We can never do that, because it will never be practicable to provide the machinery which would be required to supply the heat consumed during that short period and allow that machinery to remain idle during the balance of the year. Therefore, in order to provide a seasonal load factor, the heating of buildings by electrical energy, should only be auxiliary to steam or hot air heating systems, and the peak of the winter would be taken care of by the ordinary furnace. It would be a great relief here in Seattle if we could have a small amount of heat available in electrical form during the fall and spring months. We could operate our furnaces, then, for two or three months each year—probably two months would be all that would be required—and by following this plan, we would be enabled to provide electric energy at a rate sufficiently low to make its use practicable for heating purposes. Some of the engineers of the city having in mind the paper that was presented this morning, asked us at the University to make some experiments in designing a heater of the induction type, having a high power factor. I think there is a general feeling that resistance heaters have too large a maintenance expense, and that the induction heaters on the market at the present time have too low a power factor to make them practicable. I will describe a hot water heater, modified so as to include an electric heating element, which was built at the University, and on which we have made a series of experiments. The core is an ordinary iron pipe and is surrounded by a copper layer sweated on to the pipe, forming the secondary coil; which in turn is surrounded by a primary coil connected to the electric circuit. With that simple arrangement, we have an induction heater with a power factor of over ninety-eight and one-half per cent. I think that with a heater of this type used as auxiliary on a hot-water heating system of a house, good results could be obtained.

W. D. Peaslee: There is on the market to day a heater constructed on that identical principal, with the exception that they claim that it is not a short-circuit transformer. The big fault that I have to find with that type of heater—I made some tests on one this year—was that it is so very sensitive to voltage variations. That is, a voltage variation of two per cent as the machine is commercially manufactured at the present time, gives a current variation of something like forty per cent. You are all very familiar with the short-circuited current-voltage curve of a transformer. Unless you make the impedance of the secondary so high that you lose a great deal of the beneficial effect of low power factor, all induction heaters that I have had occasion to examine, are extremely sensitive to slight voltage variations. For instance one machine that I put under test this year was rated at 1200 watts, and if it was put on a commercial load in the city in which it was to be used, it would have fluctuated between 900 and 1700 watts, and I don't believe the power companies care to have them connected with their feeders. If it is on a flat rate they are losing money on it. While that machine can be so designed as to give a very high power factor, at the same time its characteristics are such that it is very sensitive to low-voltage fluctuation. I know the one made in Portland has some kind of a silica flux put over the coils, and the only way to hurt it is to use current enough to actually melt the apparatus.

L. F. Curtis: It may be of interest to know that this heater has practically a straight line curve between current and voltage. The reactance of the unit is so small that it has practically no effect. The iron does not become saturated and therefore has little influence on the performance. The particular unit in question was used in a seven-section radiator, and when run at about two kilowatts gave a rise of about fifty degrees above room temperature centigrade in an hour and a half. When run at one kilowatt, the temperature was maintained at approximately fifty degrees above room temperature. The power factor was uniformly above ninety-eight per cent in all of the tests run at different voltages.

R. W. Pope: One of the authors of the paper this morning gave some figures in regard to household heating, lighting and cooking, which compared very well with my experience. My house is a nine room, frame structure clapboarded and shingled outside, and heated with hot air, and lighted with gas, with an auxiliary gas burning grate in the dining room which we have found exceedingly satisfactory. We can go into the house at any time of year, light it up and have heat available. We spend about $150.00 a year for all purposes, burning about fifteen tons of hard coal at $6.50, the gas bill for all purposes averaging about $4.00 per month. If the cost of electricity is $24.00 for heating water, and $36.00 a year for cooking, that would be a total of $60.00, leaving a $90.00 margin for the heating of the house. Heating by electricity is not considered economical, compared with other methods.

E. R. Perry: I think it will be interesting to consider the use of electric water heaters in connection with the electric range. It was first suggested, as stated in this paper, that a good load factor could be secured for this service by installing the heaters on flat rate, assuming that they would be used continuously, which would have the disadvantage of adding their load to the existing peak. To eliminate this disadvantage the water heater was alternated with the entire range by a double-throw switch arrangement. That condition gave rise to a little dissatisfaction, because the people, in preparing dinner, used a great deal of hot water, drawing it all out of their tank, and the small capacity heater provided did not heat the water up again soon enough for their purposes. It was then suggested, and in some cases, they tried to alternate the hot water heater with a part of the range, and the question then rose as to what part of it. It might be operated with part of the oven of equivalent capacity, or some other part of the stove with equivalent capacity, but this was found to give the hot water peak on top of their range peak. So the proposition generally came down to the situation where it was found best to connect the water heater on a flat rate, and make the rate high enough to give a sufficient revenue, and not bother with the range at all, because a hot water heater of 500-watts capacity cannot be satisfactorily operated in connection with a range.

Prof. Magnusson mentioned the seasonal load factor in connection with heating. I do not think that electrical heating will ever be very successful, as long as it is an auxiliary to other systems of heating. The general public will not have a duplicate system of heating installed in their homes, and use electricity as an auxiliary. The output of a hydroelectric station in this section of the country usually runs greatest from the month of January to the month of July, and then falls off during the rest of the year. It is evident that the seasonal load factor, then, which would be desirable, would be to use electric heating from January until summer. Unfortunately, there are about three cold months, October, November and December, which come along, when there is not a great deal of water. In most hydroelectric systems, I dont think that a heating load, which will cater to the seasonal load factor, will do the job of heating the houses. Some arrangement will have to be worked out for electric heating, that will run any time or all the time that the people want it, and give them all the capacity they will need to keep warm.

H. F. Holland: I think possibly we will have to consider our own cities in making deductions. As engineers, you must not overlook the fact that many houses are going to be heated by electricity. I will refer particularly to Idaho. In a school house there, something like 800 kw. of heat is used. In another case, about 500 kw. Many of the houses and the hospitals are heated by electricity. You will have to consider that you are not working in Spokane, or New York, or the middle west, but you will have to consider conditions all over the country, and it is well worth your while to consider electric heat as among the necessary things to be supplied by your power systems.

H. J. Gille: There is one thing in connection with this water heating proposition that has not been touched upon. Where heaters are used without any restrictions, and the heater is just a little larger than would be required for continous operation, a sufficient diversity factor will be obtained by the heater being used only during the night.

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TEMPERATURE RISE OF INSULATED LEAD-COVERED CABLES

BY RICHARD C. POWELL

Abstract of Paper

After a brief historical note the factors that determine the rating of a cable are considered.

The thermal conductivity of a cable is expressed in terms of the volume thermal conductivity of the insulation, the surface thermal conductivity of the lead sheath, and the dimensions of the cable. The values of the thermal conductivities as given by various observers including the author are compared. A diagram is shown for readily obtaining the thermal conductivities of one-conductor cables, and tables are given of the carrying capacity of one-conductor cables for various duct temperatures and thicknesses of insulation. Factors are added so that the carrying capacity of multiple-conductor cables may be taken from these tables.

Sometimes the lead sheath of a cable carries considerable stray current. A formula is given for calculating the increased temperature due to such current.

The carrying capacity of a cable is largely determined by the thermal properties of the duct line in which it is installed. This feature is discussed briefly.

The overload or intermittent rating is calculated from a formula involving the thermal capacity of the cable multiplied by a factor. Experimental values of this factor for several types of cables are given. A formula is given to take account of variable air temperature.

Various formulas given in the paper are developed in three appendixes.

I.—Introduction

THE limitation of the current-carrying capacity of electrical conductors due to heating effects has been a subject for investigation since 1849 when Joh. Müller[1] starting with Newton's Law of Cooling, arrived at the result that, for bare wires of the same material, the current required to produce the same rise of temperature varies as the 1.5 power of the diameter. We now know this to be incorrect as the exponent is nearer 1.25. However, the subject was not really seriously considered by engineers until taken up by Forbes[2] in 1882. Since then quite a number of investigators have published data relating to the heating of wires and cables, and a very good resume—of the whole subject up to 1905 is given by Teichmüller in his "Die Erwärmung der Elektrischen Leitungen."

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[1] Glühen von Metalldrähten durch den galvanischen Strom. Bericht uber die neuesten Fortschritte der Physik. Band I.

Since Eurpoean practise is to employ armored cables buried in the earth, we find very few European data of any real practical value to American engineers desiring information on lead covered cables for a draw-in system.

It was not until 1905 when Fisher published the results of some quite extensive tests at Niagara that current ratings for lead-covered cables began to take definite shape. Based upon these tests, Fisher published in 1906 a table of current ratings, which has been quite extensively used by engineers.

This table is to be considered more as a good safe rule applicable under somewhat unfavorable conduit conditions, rather than data which enable an engineer to rate a cable intelligently in accordance with the actual conduit conditions. It is to be noted that Atkinson in 1913 at the discussion of an Institute paper by Atkinson and Fisher, gave the results of some tests in a form more suited to the use of engineers. This paper and discussion will be referred to later.

Previous to the above mentioned table by Fisher, cables were usually rated according to some rule allowing a certain number of amperes per unit area, generally thousand circular units or square inch; and Fisher's work was a very great advance.

In order to expedite matters for a subject such as cable ratings, where there is an almost endless variety of conductor sizes, insulation thickness, types of make up, etc. and at the same time make it possible to compare properly the work of various investigators, the problem must be reduced to its simplest physical terms. That is, the complexity must be reduced by considering only the independent physical constants. Once these have been established, any engineer having the dimensions of a cable, and sufficient data upon the surrounding temperature may obtain a dependable rating cable.

In searching through the available literature, the writer has found only a few papers that conform to the above requirements and which may, therefore, be a basis for proper comparison. These are:

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[2] On the Thickness of Wires Required to Carry Different Electric Currents without Overheating. *Electrician* (London) 1882.

Mie,—Über die Wärmeleitung in einem verseilten Kabel, *Elekt. Zeit.* 1905.

Melsom & Booth—The Heating of Cables with Current. *Jour. Inst. Elec. Engrs.* Vol. 47—1911.

Atkinson and Fisher—Current Rating of Electric Cables, TRANS. Am. Inst. Elec. Engrs. 1913, p. 325.

Dushman—The Heating of Cables Carrying Current. TRANS. Am. Inst. Elec. Engrs. 1913, p. 333.

The purpose of the present paper is to discuss more particularly the carrying capacity of paper-insulated cables, although it will be evident that much of what follows is applicable to cables insulated with other materials.

II—RATING OF CABLES

The rating of an insulated cable is determined by

A. —Continuous rating.

1. The maximum temperature at which the insulation may be operated without undue deterioration.
2. The thermal conductivity of the cable.
3. The thermal condition and properties of the surrounding medium, usually the air in a conduit system.

B. —Overload or intermittent rating, in addition to 1, 2, and 3 under A.

4. The thermal capacity of the cable and surrounding medium, that is, the ability of the cable to store a portion of the heat released in the conductor, and thereby, for short periods of time, to put less demand upon the cable as a dissipator of heat.

It is demonstrated in works on heat and is a fact so well known as not to require proof here that the thermal conductivity of an infinite hollow cylinder in watts per cm. of length per deg. cent. is

$$k_1 = \frac{2\pi\lambda}{ln\,\frac{d_1}{d}} \tag{1}$$

in which λ = specific thermal conductivity of the material in watts per deg. cent. per cm.

ln = Naperian logarithm

d_1 = outer diameter of cylinder

d = inner diameter of cylinder

For a cable, d_1 and d are, of course, the inner diameter of the lead sheath and the diameter of the conductor respectively.

In applying equation (**1**) to thermal measurements of cables, it is necessarily assumed that the conductor and the sheath are in very close contact with the insulation, and that there is no appreciable temperature drop from the conductor to insulation or from insulation to sheath. This assumption may not be correct; hence it is always advisable to obtain values for λ from measurements on actual cables instead of from the insulation taped up on cylinders, etc. It may be said, however, that equation (**1**) when applied to cable measurements gives consistent values.

The surface thermal conductivity of the lead sheath to air is, in watts per cm. of length per deg. cent.

$$k_2 = \pi \, d_3 \, h \tag{2}$$

where h = specific surface thermal conductivity for lead to air in watts per deg. cent. per cm^2.

d_3 = outer diameter of the sheath in cm.

The thermal conductivity of the cable, that is, the watts per cm. per deg. cent. difference in temperature of the conductor and the air surrounding the lead sheath is

$$k = \frac{k_1 \, k_2}{k_1 + k_2} \tag{3}$$

This expression is at once recognized as that giving the electrical conductivity of two conductors in series and the analogous thermal conductors in series are the insulation and the lead sheath.

It is now readily seen that it is only necessary to agree upon values for λ and h in order to establish ratings for all one-conductor cables. Various observers have obtained somewhat widely differing values for these.

VALUES FOR λ AND h.

Observer	λ	h
	for saturated paper	for lead sheaths
Melson and Booth	0.00102 to 0.00134	0.00088 to 0.00155
Atkinson and Fisher	0.00100 to 0.00115	0.00083 to 0.0096
Powell	0.00081 to 0.00114	0.00090 to 0.0011
Dushman		0.00081 to 0.0011
[1]Symons & Walker	0.00142 to 0.0017	

[1] The Heat Paths in Electrical Machinery, *Jour. Inst. Elec. Engrs.*, Vol. 48. These values were obtained by wrapping the paper on a copper cylinder which was then placed in an oil bath.

It will be apparent, after examining into the conditions of the cables tested, that the above values are in reasonable agreement. Atkinson and Fisher state that they tested new cables with bright lead sheaths, and Dushman presumably made his tests upon new cables. The writers' values are from tests on old cables taken from service as well as on new cables, and it is to be especially noted that the variation in λ is greater than that given by any other observer, excepting Melson and Booth, and the writer is unable to state anything regarding the age of the cables tested by them.

The values 0.00114 for λ and 0.0009 for h were found for new cables with well saturated paper and bright sheaths, and are in very close agreement with the values by Atkinson and Fisher.

The value $h = 0.0011$ found by the writer for lead with discolored and roughed surface is the same as Dushman's value for lead painted black. It is, of course, well known that lead under these conditions is a better thermal dissipator.

The value 0.00081 for λ was measured upon a piece of 500,000-cir. mil. 5/32-in. lead cable which had been in service for a number of years. The paper was in excellent condition and of a very strong quality. It was so dry, however, that there was not a trace of free oil and it had the slightly translucent appearance of thick oiled paper. 'The writer has tested a number of pieces of old cables taken from service and the values for λ all ranged from 0.00081 to 0.00092, none showing so good values as for new, well saturated cables.

In the writer's opinion the degree of saturation and hence the age (since there is more or less continual drying action in service) has an important bearing upon the carrying capacity of paper insulated cables.

THERMAL CONDUCTIVITIES IN WATTS PER FT. PER DEG. CENT. OF NEW AND OLD PAPER-INSULATED CABLES

Size cir. mils	Thickness of insulation	Observer	
		Atkinson & Fisher A.I.E.E. 1913	Powell
500000	4/32	0.21	
500000	5/32		0.19
1,000000	4/32	0.275	0.26
1,000000 (new)	4/32		0.308
1,150000	4/32	0.31	0.318

Although the thermal conductivity of the paper decreases with service, that of the lead increases, and the two effects just about balance, so that an old cable has nearly as good carrying capacity as a new one.

The values due to Atkinson and Fisher are for new cables and are those calculated from the table given in the discussion of their previously mentioned paper and increased by 12 per cent to agree with their test values. Except as noted, the writer's values are for old cables.

Values of λ and h to be Used in Determining Carrying Capacity. The above mentioned table recommended by Atkinson and Fisher is based upon $\lambda = 0.00100$ and $h = 0.000833$.

It is believed that the value of λ is too high for cables after several years service, and h is too low even for new cables after being exposed to the air for a few months. The writer, therefore, proposes ratings for paper cables based upon $\lambda = 0.00085$ and $h = 0.001$. First class cables, particularly, in a short time after installation, will usually show 15 per cent to 20 per cent greater carrying capacity than that calculated from these values, and most old cables of the same quality, 10 per cent greater. However, allowance must be made for paper and saturation which may not be of the best, for inaccuracies of measurements on cables in a conduit system, and some uncertainty as regards heating due to sheath currents.

If t is the thickness of insulation in inches and $\lambda = 0.00085$, equation (**1**) becomes

$$k_1 = \frac{2\,\pi \times 0.00085}{ln\left(1 + \frac{2t}{d}\right)} \times 30.5$$

$$= \frac{0.1625}{ln\left(1 + \frac{2t}{d}\right)}$$

watts per ft. per deg. cent. (**4**)

Similarly, equation (**2**) becomes, if d_3 is in inches,

$$k_2 = \pi\, d_3 \times 0.001 \times 6.45 \times 12$$
$$= 0.244\, d_3 \text{ watts per ft. per deg. cent.} \qquad (\mathbf{5})$$

These two equations suggest a comparatively simple diagram for obtaining k, the thermal conductivity of the cable. Such a diagram is Fig. 1, proof of which is given in Appendix I. To use the diagram proceed as follows:

Follow the ordinate through the given value of $\frac{2t}{d}$ to its intersection with the curve C, thence horizontally to the scale at the left. Through this point on the vertical scale and the value for d_3 on the lower horizontal scale pass the edge of a transparent triangle or straight edge, and the intersection of this with the line L is k read off on the vertical scale.

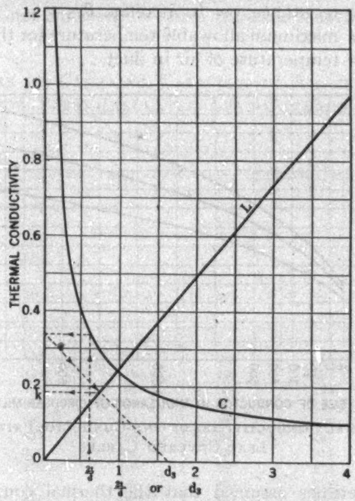

Fig. 1—Diagram Giving Thermal Conductivities of One-Conductor Paper-Insulated Lead-Covered Cables.

With the help of this diagram, the three curves in Fig. 2 have been drawn. These curves give the thermal conductivities of one-conductor paper cables for various sizes of conductors and three thicknesses of insulation, viz. 4/32 in.; 8/32 in.; and 16/32 in. Values for any intermediate thickness of insulation may be readily interpolated.

As a maximum safe temperature for saturated paper 85 deg. cent., the value allowed in the Rules of the Institute may be accepted with every assurance that it is conservative and does not represent the maximum temperature that this material will stand without deterioration. The Institute Rules call for a reduction from 85 deg. cent. of one degree for each thousand volts of operating voltage.

The maximum current carrying capacity, or the rating of a cable is given by

$$W_\theta = I^2 r_\theta = k\,(\theta - \theta_d) \qquad (6)$$

in which I = the current in amperes

W_θ = watts lost per ft. at temp. θ

r_θ = resistance, per ft. at temp. θ

θ = maximum allowable temperature for the conductor

θ_d = temperature of air in duct.

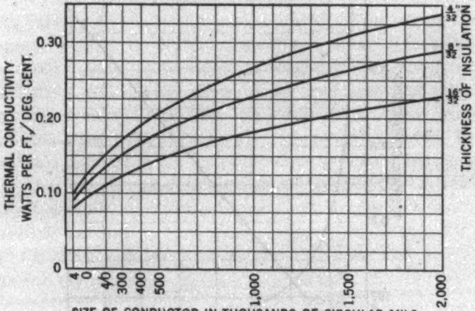

FIG. 2—THERMAL CONDUCTIVITIES OF ONE-CONDUCTOR PAPER-INSULATED LEAD-COVERED CABLES

It is sometimes assumed that the thermal conductivity of paper has a positive temperature coefficient comparable in value to the negative temperature coefficient of copper, so that the increase in loss due to the latter may be neglected. In order to check this point, the writer made the following test. The copper core was removed from a piece of 1,500,000 cir. mil 7/16 in. paper and $\frac{1}{8}$-in. lead cable about 75 cm. long. A heating coil was wound on a piece of insulated pipe and covered with asbestos taping to such a diameter as just to fit snugly into the space formerly occupied by the copper. This core was then wound with fine copper wire to be used as a thermometer coil, which was in rather good contact with the paper when the core was finally slipped into place. To guard against the escape of heat at the ends, they were filled for several inches with felt.

The values of λ for core temperatures of 75.5 deg. cent. and 118 deg. cent. differed by less than 2 per cent. The writer, therefore, concludes that the above assumption is incorrect. Moreover, it is to be particularly noted that the error in neglecting the temperature coefficient of copper is not on the safe side. In the following tables $\frac{1}{8}$-in lead has been assumed. Although the smaller cables invariably have thinner lead, the difference from $\frac{1}{8}$ in. is not sufficient to cause appreciable error.

III. TABLES OF CARRYING CAPACITY, IN AMPERES, OF ONE-CONDUCTOR PAPER-INSULATED LEAD-COVERED CABLES.

TABLE I.

INSULATION 4/32 IN. WORKING PRESSURE 750 VOLTS. MAXIMUM TEMPERATURE 85 DEG. CENT.

Size	Temperature of air in duct deg. cent.				
	30	40	50	60	70
4	133	120	106	90	70
3	154	139	122	104	80
2	181	164	144	122	95
1	200	182	160	136	105
0	240	220	192	163	126
2-0	277	250	220	187	145
3-0	320	290	256	217	168
4-0	376	340	300	254	197
250M	418	380	333	282	219
300	475	430	379	320	248
400	570	515	454	385	298
500	670	608	535	454	351
750	870	790	695	590	456
1000	1070	970	855	725	560
1250	1240	1120	990	840	650
1500	1410	1275	1125	950	735
2000	1700	1535	1355	1150	890

TABLE II.

Insulation 8/32 In. Working Pressure 5000 Volts. Maximum Temperature 80 Deg. Cent.

Size	Temperature of air in duct. Deg. cent.				
	30	40	50	60	70
4	125	112	97	79	56
3	145	129	112	91	64
2	166	149	129	105	74
1	181	162	140	115	81
0	214	192	166	135	96
2-0	251	225	195	159	112
3-0	290	259	225	183	130
4-0	339	303	262	214	151
250M	371	332	288	235	166
300	431	385	333	272	192
400	519	464	402	328	232
500	610	545	472	386	273
750	785	702	609	497	352
1000	955	855	740	605	427
1250	1100	980	850	695	490
1500	1255	1125	970	795	560
2000	1510	1350	1170	955	675

TABLE III.

Insulation 16/32 In. Working Pressure 15,000 Volts. Maximum Temperature 70 Deg. Cent.

Size	Temperature of air in duct. Deg. cent.			
	30	40	50	60
4	107	93	76	53
3	122	106	86	61
2	139	120	98	70
1	152	132	108	76
0	181	157	128	90
2-0	208	181	147	104
3-0	239	207	169	120
4-0	284	246	201	142
250M	312	270	221	156
300	351	305	248	175
400	420	364	297	210
500	490	423	345	245
750	632	548	447	316
1000	766	664	542	383
1250	900	780	635	450
1500	1015	880	720	510
2000	1225	1060	865	610

IV. CARRYING CAPACITY OF MULTIPLE-CONDUCTOR CABLES

The preceding tables may be used for multiple-conductor cables by applying the following factors to the carrying capacity of one-conductor cables having the same total thickness of insulation.

Number conductors	Type of cable	Multiply one conductor capacity by
2	Flat or Figure 8	87 per cent
2	Round	80 do
2	Concentric	75 do
3	Round	70 do
3	Oval Sector	77 do
3	Cloverleaf Sector	80 do
4	Round	67 do

Thus, the carrying capacity of a 4/32 × 4/32-in. round, three-conductor cable is 70 per cent of that for an 8/32-in. one-conductor cable.

The subject of multiple conductor cables is treated more fully in Appendix II.

V. INCREASE OF TEMPERATURE DUE TO SHEATH CURRENTS

It happens, not infrequently, that cable sheaths carry considerable current. This current may be stray railway, or neutral or currents induced by alternating currents in neighboring one-conductor cables.

Let w = watts per ft. loss in conductor

w' = watts per ft. loss in sheath

k, k_1, and k_2 = thermal conductivities, for cable, conductor to sheath, and sheath to air, respectively.

θ = conductor temperature above initial

θ' = sheath temperature above initial

Then $w = k_1 (\theta - \theta')$

$w + w' = k_2 \theta'$

Eliminating θ' we have

$$\theta = \frac{w}{k} + \frac{w'}{k_2}$$

or, the temperature of the conductor is increased by the amount $\frac{w'}{k_2}$, which is the temperature the sheath would have with the same current in the sheath but no current in the conductor.

As an example; a 1,000,000-cir. mil 4/32-in., $\frac{1}{8}$ in. lead one-conductor cable which has a sheath resistance of 0.00017 ohms per ft. will operate at an increase in temperature of 5 deg., 17 deg. and 40 deg. with sheath currents of 100 amperes, 200 amperes and 300 amperes respectively. The effect of small or moderate sheath currents may be neglected, but large currents must be avoided.

VI. Cables in Duct Lines

The carrying capacity of a cable is largely determined by the thermal properties of the duct line in which it is installed, and hence, will vary greatly with type of construction and character of soil. In order to determine the proper carrying capacity of cables with any degree of reliability, it is necessary to make a temperature survey of the conduit system. Or, at least, sufficient data must be gotten covering the various types of construction and soil conditions to enable one to make a reasonably accurate estimate of temperatures.

It will be found that the thermal conductivity of a duct line is a constant, and is

$$k = \frac{w}{\theta_d - \theta_a} \text{ watts per ft. per deg. cent.} \qquad \textbf{(13)}$$

where w = total watts per ft. loss in duct lines.
θ_d = mean temperature of air in ducts
θ_a = temperature of air at surface of street

This equation will apply after the temperatures in the ducts have become steady, usually only after one or two weeks. It is to be noted that the temperature of the external air has an important bearing upon the subject and that, under otherwise similar conditions, a duct line will run much warmer in summer than in winter.

In practise, loads are seldom steady; hence, the temperature of the air in ducts follows, more or less closely, the load variations, although it will be found that the earth directly in contact with the conduit changes only with the seasonal variation of load.

The problem may conveniently be divided into two parts; viz., one having to do with heat transference from the air in the ducts to the earth directly in contact with the conduit, and the other with transference from the earth to the air at the surface.

For the first, the thermal conductivity is

$$k_d = \frac{w_d}{\theta_d - \theta_s} \text{ watts per ft. per deg. cent.} \qquad \textbf{(14)}$$

In this, w_d = maximum watts per ft. loss at stationary maximum temperature θ_d for air in ducts.

θ_s = soil temperature.

For the second, we have

$$k_s = \frac{w_s}{\theta_s - \theta_a} \text{ watts per ft. per deg. cent.} \qquad \textbf{(15)}$$

where w_s = average watts per ft. loss for a given load cycle.

For most loads the cycle is probably a week.

All thermal measurements on duct lines should be made midway between manholes, as this is the warmest point. Soil under pavements which are a considerable distance from unpaved sections rarely has the variation in moisture content found in soil under unpaved streets. Hence, measurements in soil under pavements as above may be made at almost any time of the year, but in other soil should be taken at the dryest season.

The losses w_d and w_s may be calculated from the station load reports, and θ_d is taken with a recording thermometer. Measurements for θ_d should be taken in several ducts, particularly if there is a large number in the run.

After k_d and k_s have been obtained the effect of change in loading for the cables already installed, or effect of additional cables may be calculated.

Let w_d' be the maximum duct loss, and w_s' the mean loss over the cycle for the whole conduit, both in watts per ft. after the change.

Then the new soil and duct temperatures are:

$$\theta_s' = \frac{w_s'}{k_s} + \theta_a$$

$$\theta_d' = \frac{w_d'}{k_d} + \theta_s' = \frac{w_d'}{k_d} + \frac{w_s'}{k_s} + \theta_a$$

It is hoped that the preceding discussion of duct line temperatures may assist in forming a clear conception of the physical principles involved. For only in this way may we expect to make a duct line in any degree, amenable to design as a dissipator of heat. The writer does not wish to leave the slightest impression, however, that judgment and experience are not of the highest importance in designing duct lines and may be replaced by some equations and a table of data. But unless backed up with quantitative information, "judgment and experience" are apt to be nothing but snap judgment and mental impressions.

If the large investments in duct lines and cables are to be operated with the greatest economy and reliability, it is very necessary that we increase materially our rather meager supply of information on the question of heating in conduit systems.

VII—Overload or Intermittent Rating

If a constant load, in amperes, is applied to a cable, the temperature rise of the conductor, at any time after application of the load, is given by the equation

$$\theta = \Theta\,(1 = \epsilon^{-\beta t}) = \frac{w}{k-\alpha w}\left(1-\epsilon^{-\frac{k-\alpha w}{c}t}\right) \tag{11}$$

in which θ = temperature rise above initial temperature at time t,

Θ = final temperature rise,

ϵ = base of Naperian logarithms,

$\beta = \dfrac{k-\alpha w}{c}$ = constant,

t = time in hours.

w = watts loss per ft. at initial temperature.

α = temperature coefficient of copper referred to initial temperature.

c = constant depending upon thermal capacity of cable.

It is sometimes assumed that c is equal to the total thermal capacity of the cable, which is, of course, assuming that the rate of temperature rise is the same for all parts of the cable. This assumption is incorrect. It is at once apparent, for example, that the rate of temperature rise of the lead sheath is not so great as that of the conductor, particularly, for heavily insulated cables. The error is not appreciable for small cables, but for large well insulated cables the above assumption leads to results which are in error on the danger side, that is give too small a value for β and hence a lower temperature rise in a given time

We may put

$$c = c_1 + p\,(c_2 + c_3) \tag{12}$$

where c_1 = thermal capacity of the conductor in watt-hr. per ft.
c_2 = thermal capacity of the insulation in watt-hr. per ft.
c_3 = thermal capacity of the lead sheath in watt-hr. per ft.
p = constant, depending upon the type of cable.

Some values for p as found by the writer follow:

EXPERIMENTAL VALUES FOR CONSTANT p.

No. conductors	Size conductor	Thickness of insulation	Thickness Lead	p
1	4/0	7/16 Paper	⅛	0.81
	500,000	5/32 "	⅛	0.70
	1,000,000	4/32 "	⅛	0.70
	1,500,000	4/32 "	⅛	0.77
3	4/0	13/64×13/64 Paper	⅛	0.595
	250 M Submarine	(6/32 rubber + 2/32 Var. Cl.) × 5/32 Var. Cl.	5/32 + 41 No. 4 Steel Armor Wires	0.59

From data given by Dushman for a one-conductor 250,000, 4/32-in. rubber cable, p was found to be 0.80.

Hence, for practical purposes, it appears that we may put $p = 0.75$ for one-conductor and $p = 0.60$ for three-conductor cables.

The following quantities may be used in calculating the thermal capacity of a cable.

THERMAL CAPACITY IN WATT-HR. PER INCH CUBE

Copper, iron, steel	0.01525
Lead	0.0064
Rubber	0.00625 (Dushman
Paper	0.0047

For a further discussion of equations (**11**) and (**12**) see Appendix III.

In Fig. 3, is shown some test curves together with those plotted from equations of the form of (**11**).

With the assistance of a curve, Fig. 4 giving $(1 - \epsilon^{-\beta t})$ for various values of βt, we may very readily obtain the temperature at any time t, provided the final temperature Θ, and the

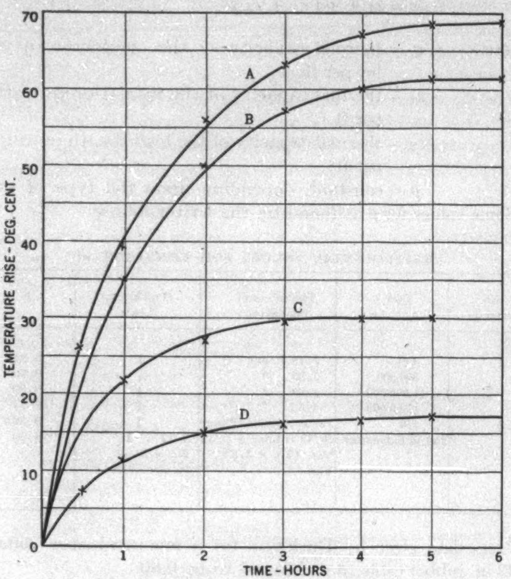

FIG. 3—RATE OF TEMPERATURE RISE OF CABLES

Curve	Type of cable	Load amps.	Equation
A	4/0 3-conductor round 13/64 × 13/64 paper ⅛" lead	300	$\theta = 69\,(1 - \epsilon^{-0.83\,t})$
B	1,500,000 cir. mil 1-conductor 4/32 paper ⅛ lead	1500	$\theta = 62\,(1 - \epsilon^{-0.86\,t})$
C	500,000 c.m. 1-conductor 5/32 paper ⅛ lead	500	$\theta = 30\,(1 - \epsilon^{-1.4\,t})$
D	250,000 c.m. 3-conductor submarine (6/32 rubber + 2/32 var. cl.) × 5/32 var. cl. 5/32 lead and 41 No. 4 steel armor wires.	310	$\theta = 17\,(1 - \epsilon^{-1.05\,t})$

Points calculated from equations shown X.

time constant β are known. These, however, may easily be computed with the preceding equations and data.

For example, let it be required to find the time for a 1,000,000-cir. mil 4/32-in. paper cable to reach 85 deg. cent. starting at a temperature of 40 deg. cent. with a load of 1200 amperes. It is assumed that the temperature of the surrounding medium remains constant at 40 deg.

w, at 40 deg., = 17.0 watts per ft.
α (40 deg. reference) = 0.0036
$k = 0.27$
$c = 0.21$

$$\Theta = \frac{w}{k - \alpha w} = \frac{17.0}{0.21} = 81 \text{ deg. cent.}$$

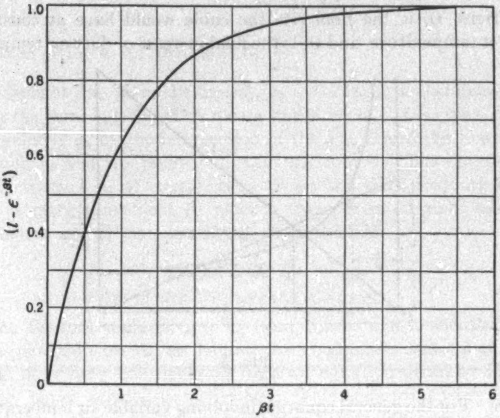

FIG. 4—CURVE OF $(1 - \epsilon^{-\beta t})$

The rise is to be 45 deg., hence

$$\frac{45}{81} = (1 - \epsilon^{-\beta t}) = 0.555$$

From the curve (Fig. 4), we find $\beta t = 0.8$

But $\beta = \dfrac{k - \alpha w}{C} = \dfrac{0.21}{0.21} = 1.0,$

and therefore, $t =$ 0.8 hour, or about 50 minutes.

In general, the duct temperature increases simultaneously with that of the cable, and usually at approximately the same rate. If this increase is small, that is, 5 or 10 deg., we may simply add this increase to the final temperature. For instance, in the above example, if the final duct temperature had been 50 deg. instead of 40 deg., we should have had $\Theta = 91$ deg. and the time about 40 minutes.

If the increase in duct temperature is large, the temperature coefficient of copper should not be neglected. A more correct value for the final rise of a cable is

$$\Theta = \Theta_1 + \frac{k}{k - \alpha\, w}\,\Theta_2$$

Here, Θ_1 is the final rise the cable would have at constant duct temperature, and Θ_2 is the final increase of duct air temperature. For the general equation involving variable air temperature see Appendix III.

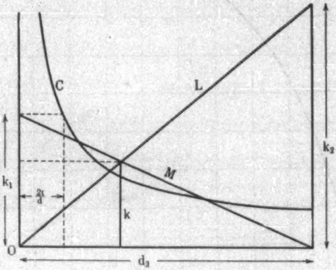

FIG. 5

Many of the cable tests, from which the data given above were taken, were made by the Laboratory Department of the Pacific Gas and Electric Company, San Francisco, and the writer desires to thank Mr. Knopp, the Superintendent and his staff for the very careful manner in which these were done.

APPENDIX I.

DIAGRAM FOR FINDING THERMAL CONDUCTIVITIES OF ONE-CONDUCTOR CABLES

This construction is based upon a well known geometric construction which is sometimes used for finding graphically the circuit resistance of two resistances in parallel.

Two perpendicular distances k_1 and k_2 (Fig. 5) are erected at the ends of a given line and the top of each is joined to the foot of the other by a straight line (the lines L and M in the figure). The perpendicular dropped upon the base line from the intersection of these two lines (k in the figure) is connected to k_1 and k_2 by the relation

$$\frac{1}{k} = \frac{1}{k_1} + \frac{1}{k_2}, \text{ or } k = \frac{k_1\,k_2}{k_1 + k_2}$$

By plotting the equation $k_1 = \dfrac{0.1625}{ln\left(1 + \dfrac{2t}{d}\right)}$ the curve C is obtained giving k_1 for any value of $\dfrac{2t}{d}$.

The straight line (L in the figure), $k_2 = 0.244\,d_3$, is next drawn. After the point k_1 is found by means of the curve C, k is given, for any value of d_3 by the intersection of the line L and the line M through k_1 and the point P distant d_3 from 0. The thermal conductivity k is, of course, read off on the same scale as k_1.

It is more convenient to place a transparent straight edge through k_1 and d_3 than actually to draw the line.

APPENDIX II

MULTIPLE-CONDUCTOR CABLES

The thermal conductivity, k_1 from conductors to sheath for multiple-conductor cables having the conductors laid up in a single layer may be calculated from an equation given by Mie in his paper previously mentioned. This equation covers the usual two-, three-, and four-conductor cables for power purposes, and is

$$k_1 = \frac{2\,n\,\pi\,\lambda}{ln\,[(1 - \alpha\,\beta) + \sqrt{(1 - \alpha^2)\,(1 - \beta^2)}} \text{ watts per ft. per deg. cent.} \qquad (7)$$

in which n = number of conductors

$\alpha = \left(\dfrac{R_1}{R_2}\right)^n$

$\beta = q\,\alpha\,,\; q = \dfrac{R_1 - (n+1)\,r}{R_1 + (n-1)\,r}$

r = radius of conductors

R_1 = radius of circle circumscribing the conductors

R_2 = inner radius of lead sheath

R_1 and R_2 depend upon the size and number of conductors and thickness of insulation.

If t_1 and t_2 are the thicknesses of insulation for conductors and belt respectively, then

$$R_2 = R_1 + t_1 + t_2$$

and $R_1 = 2r + t_1$, for two-conductor round cables

$$R_1 = \frac{2(r + t_1)}{\sqrt{3}} + r = 2.16r + 1.15t_1 \text{ for three conductors}$$

$$R_1 = \frac{2(r + t_1)}{\sqrt{2}} + r = 2.42r + 1.41t_1 \text{ for four conductors}$$

The quantity $(1 - \alpha\beta) + \sqrt{(1 - \alpha^2)(1 - \beta^2)} \equiv m$ is approximately a constant for a given type of cable, and the following values may be used,

1.90 for two conductors, and

1.96 for three and four conductors.

Equation (7) may, therefore, be somewhat simplified. We may put

$$R_1 = (a + b)\, r$$

whereupon, $\alpha - \beta = \alpha\,(1 - q) = \alpha\,\dfrac{2\,n}{a + b + n - 1} = \alpha\,C,$

and, finally,
$$k_1 = \frac{2\pi\lambda}{l\,n\,\dfrac{R_2}{R_1\sqrt[n]{\dfrac{C}{m}}}} \qquad (8)$$

That is, a multiple-conductor cable has the same thermal conductivity as a one-conductor cable of the same outside sheath diameter and a conductor diameter equal to

$$2\,R_1\sqrt[n]{\frac{C}{m}} = 2f\,R_1$$

In practise, it is scarcely worth while to make calculations for the various sizes of conductors and thicknesses of insulation as it will be discovered that the factors for applying to one-conductor cable ratings do not differ by more than 5 per cent. To find the carrying capacity of a multiple-conductor cable, apply the following percentages to the carrying capacity of a one-conductor cable having the same total thickness of insulation.

No. Conductors	Multiply One-conductor Capacity by
2	80 per cent
3	70 " "
4	67 " "

TWO-CONDUCTOR FLAT AND THREE-CONDUCTOR SECTOR CABLES

In addition to the above there are frequently used two-conductors flat and figure 8, and multiple sector cables. Sector cables are of two types, oval and clover leaf. The oval is laid up with fillers and the clover leaf without. It is evident that sector cable has greater carrying capacity than round, and that the clover leaf is somewhat better in this respect than the oval. The writer has found by test that a 4/0, 13/64-in. × 13/64-in. paper, three-conductor, oval sector cable has 12 per cent better carrying capacity than a similar round cable.

It is believed that the following percentages may safely be applied to two-conductor flat and three-conductor sector cables.

Type of Cable		Multiple One-conductor Capacity by
2 Conductor, flat		87 per cent
3 "	Oval sector	77 " "
3 "	Clover leaf sector	80 " "

TWO-CONDUCTOR CONCENTRIC CABLE

Concentric cable is sometimes used for direct-current feeders where duct capacity is limited.

Let d = diameter of inner conductor,
d_1 = inner diameter of outer conductor
d_2 = outer diameter of outer conductor
d_3 = inner diameter of sheath
d_4 = outer diameter of sheath

$$a = \frac{\text{total area of both conductors}}{\text{area outer conductor}}$$

The slightly increased loss in the inner conductor due to operating at a little higher temperature than the outer may be neglected. Sometimes the area of the inner conductor is made larger in area than the outer.

The thermal conductivity is

$$k = \frac{(a\,k_1)\cdot k_2'}{(a\,k_1)+k_2'} \text{ watts per ft. per deg. cent.} \tag{10}$$

in which $k_2' = \frac{k_2\,k_3}{k_2+k_3}$,

$$k_1 = \frac{2\,\pi\,\lambda}{l\,n\,\frac{d_1}{d}}$$

$$k_2 = \frac{2\,\pi\,\lambda}{l\,n\,\frac{d_3}{d_2}}$$

$$k_3 = 0.244\,d_4$$

The carrying capacity of a two-conductor concentric cable with conductors of equal area may be taken as 75 per cent of that for a one-conductor cable.

Increasing the size of the inner conductor is of very little advantage, for example, a concentric cable with 1,250,000 cir. mil inner conductor and 1,000,000 cir. mil out has only about 9 per cent greater carrying capacity than a cable with both conductors 1,000,000 cir. mil.

APPENDIX III.

RATE OF TEMPERATURE CHANGE OF A ONE-CONDUCTOR LEAD-COVERED CABLE

In order to develop the theory of temperature rise of cables, one might follow along the usual lines of mathematical physics, but it will soon be evident that the mathematical difficulties are such that a rigorous development is not suitable for engineering purposes. The following discussion may be of interest.

It may be shown experimentally that the following equation, which is only approximately true but sufficiently so for engineering use, gives the rise of temperature of any part of a one-conductor cable from the time load is first applied:

$$\theta_r = \Theta_r\,(1 - \epsilon^{-\beta t}) \tag{1}$$

in which θ_r = temperature at time t and at any point P between the conductor and the lead sheath distant r from the axis of the cable, including also the conductor and the sheath

Θ_r = final temperature (at $t = \infty$) at the point P.

ϵ = base of Naperian logarithms

β = constant for any given cable and loading.

With this assumption, the quantities Θ_r and β may be expressed in terms of known physical constants and the dimensions of the cable.

In the following, all temperatures are in degrees centigrade above the initial temperature assumed constant.

Let w = watts per cm. loss in cable at initial temperature.

α = temperature coefficient of copper referred to initial temperature.

θ = temperature of conductor at time t

θ_r = temperature of insulation at time t at point distant r from cable axis.

θ_b = temperature of lead sheath at time t

Θ = final temperature of conductor.

Θ_r = final temperature of insulation at point distant r from cable axis.

Θ_b = final temperature of lead sheath.

C_1 = thermal capacity of conductor in watt-hr. per cm.

C_2 = thermal capacity of insulation in watt-hr. per cm.

C_3 = thermal capacity of sheath in watt-hr./cm.

ρ = density of insulation, grams per cm.^3

c = specific heat of insulation watt-hr. per gram.

λ = volume thermal conductivity of insulation; watts per deg. per cm.

h = surface thermal conductivity of sheath to air, watts per deg. per cm.^2

α = radius of conductor

b = inner radius of sheath

d_3 = outer diameter of sheath

The following equation expresses mathematically the fact that the heat generated in the conductor is equal to that stored in the copper, insulation and lead plus that dissipated at the surface of the lead.

$$w\,(1+\alpha\,\theta) = C_1\frac{d\,\theta}{dt}+\int_a^b 2\,\pi\,\rho\,c\,r\,\frac{d\,\theta_r}{dt}\cdot dr+C_3\frac{d\,\theta_b}{dt}+\pi\,h\,d_3\theta_b \tag{2}$$

Differentiate equation (**1**) and

$$\left.\begin{aligned}\frac{d\,\theta}{dt} &= \beta\,\Theta\,\epsilon^{-\beta t},\\ \frac{d\,\theta_r}{dt} &= \beta\,\Theta_r\,\epsilon^{-\beta t},\\ \text{or,}\qquad \frac{d\,\theta_r}{dt} &= \frac{\Theta_r}{\Theta}\cdot\frac{d\,\theta}{dt}.\end{aligned}\right\} \tag{3}$$

Substituting this value for $\frac{d\,\theta_r}{dt}$ in (**2**) and evaluating the integral, we find after substituting

$$k_1 = \frac{2\pi\lambda}{ln\,\frac{b}{a}},\ k_2 = \pi\,d_3\,h,\ \text{and}\ k = \frac{k_1\,k_2}{k_1+k_2}$$

that

$$w\,(1+\alpha\,\theta) = \left[\,C_1+\rho\,c\left\{\pi\,(b^2-a^2)\left(1+\frac{k}{4\,\pi\,\lambda}\right)-\frac{\pi\,k\,b^2}{k_1}\right\}+C_3\,\frac{k_1}{k_1+k_2}\right]\frac{d\,\theta}{dt}+k\,\theta$$

Or, we may write this in the form:

$$w\,(1+\alpha\theta) = C\,\frac{d\theta}{dt}+k\,\theta \tag{4}$$

in which

$$C = C_1+p_2C_2+p_3C_3$$

$$p_2 = \left(1 + \frac{k}{4\pi\lambda}\right) - \left(\frac{k\,b^2}{k_1\,(b^2 - a^2)}\right)$$

$$p_3 = \frac{k_1}{k_1 + k_2} = \frac{k}{k_2}$$

In practise, we may approximate further and put

$$C = C_1 + p(C_2 + C_3)$$

The integral of (**4**) is

$$\theta = \frac{w}{k - \alpha\,w}\left(1 - \epsilon^{-\frac{k - \alpha\,w}{c}\,t}\right) \qquad \textbf{(5)}$$

Variable Air Temperature

Since the change of air temperature in a duct line or other location where cables are usually installed is due to increased load on the cables, an equation of form (**1**) will express the temperature change for the air. Let this equation be

$$\theta_a = \Theta_a\,(1 - \epsilon^{-\beta_a t}) \qquad \textbf{(6)}$$

in which the temperatures as before are those above the initial temperature.

The equation of heat balance for the cable now becomes

$$w\,(1 + \alpha\theta) = C\,\frac{d\theta}{dt} + k\,(\theta - \theta_a) \qquad \textbf{(7)}$$

and the solution is

$$\theta = \Theta_1\,(1 - \epsilon^{-\beta t}) + \frac{k\,\Theta_a}{C\,(\beta - \beta_a)}\,(1 - \epsilon^{-\beta_a t}) - \frac{k\,\beta_a\,\Theta_a}{C\,\beta\,(\beta - \beta_a)}\,(1 - \epsilon^{-\beta t}) \qquad \textbf{(8)}$$

In which

$$\Theta_1 = \frac{w}{k - \alpha w}$$

For most practical purposes, one may put $\beta_a = \beta$ so that (8) becomes

$$\theta = \left(\Theta_1 + \frac{k}{k - \alpha\, w}\,\Theta_a\right)\,(\,1 - \epsilon^{-\beta t}\,) \tag{9}$$

That is, the final temperature of the conductor is greater by the amount $\frac{k}{k - \alpha\, w}\,\Theta_a$ over what it would have been with constant air temperature.

Discussion on "Temperature Rise of Insulated Lead-Covered Cables" (Powell), Seattle, Wash., Sept. 5, 1916.

M. T. Crawford: Reference is made to cables in duct lines, stating it will be found that the thermal conductivity of a duct line is constant. A formula is given for applying this, considering the temperature of the air in the ducts, and the temperature of the air at the surface of the street. There is one thing which should be considered in a city where an underground system of steam heating service is maintained. Steam mains or steam service pipes frequently parallel and cross duct lines, and the close proximity of the steam pipe has quite an effect on the cables or the duct lines. This will be much greater in winter than in summer. If the steam line belongs to another utility, the exact location of it with reference to the duct line may not be very definitely known. Sometimes a steam line crossing a duct line at right angles may create a hot spot in a location which would not be noticed at man holes, or not easily discovered. This matter should be considered in addition to the temperature of the air in the ducts, and at the surface of the street.

L. T. Merwin: I think, perhaps, the experience of the Northwestern Electric Company in Portland, along the line Mr. Crawford has just spoken of, has been a little more severe, possibly, than he has had here, owing to the type of construction, in the alignment of the steam heating mains with the electric lines. Fortunately, or unfortunately, as the future may determine, our electric duct lines in those streets that carry steam heating mains, lie over or beside them. We have noticed no discomfort electrically or physically in handling the operation and maintenance of the system under ordinary conditions. But in our last seasonal high water period, which came this year in July, rather than, as usual, in June, owing to the late spring, we had a rather distressing set of conditions to combat. It was the first time, since our system was installed, that we had had very high water. As a matter of fact, the flood stage this year, reached a point that had been reached previously only twice since the weather bureau has been keeping its records. While, at the present time, for instance, the state of the Willamette River is, on United States Engineers' gauge, approximately six feet, it rose to the level of 23.9 feet on July 4th and 5th. That put the steam lines under water. So far as I know, it is practically impossible to make the installation of steam lines thoroughly waterproof, although, probably if we had forseen just the situation that subsequently arose, we might have obviated some of the difficulty; but the fact remains that the steam lines were under water, and subject to a considerable infiltration. The electric duct lines overlying the steam pipes were then subjected to a very high temperature, due to the fact that the ground was thoroughly saturated, and the moisture in the ground was heated not merely to the boiling point of water, but practically to the temperature of the pressure we are carrying,

Vol. 35
1916

namely, about six or seven pounds,—say 227 or 228 degrees Fahrenheit. The electric duct lines are of vitrified clay, the joints presumably not the best especially in one street, where the construction was carried on with heavy interurban trains running beside it, so that there was more or less settlement when the lines were laid. We had the peculiar anomaly of suffering from high water and yet being face to face with the necessity of keeping the overlying electric duct lines flooded artificially with cold water in order to keep them cool. Our paper insulated cables were subjected to a temperature of 228 degrees, even imagining that the cables were carrying no current. Now, over the evening peak, the cables carried a current which would normally bring them, for the time of the peak, to something approaching, we will say, 150 degrees Fahrenheit. Then, in addition to this, they were subjected to a flat temperature of 228 degrees. I should say that in the neighborhood of 14,000 feet of lead covered, paper insulated cable was affected, and of that, we had failure in but one block. During the trouble, and subsequent to it, I have been endeavoring to find data that might be available covering the quantitative value of the deterioration that might have taken place. I have been unable to find anything in our literature on the subject to give me a hint as to what I might expect as to this quantitative value. I do know that in this one block, we had one cable fail. Unquestionably, we must attribute it to the excessive temperature, but whether it was augmented by other conditions, I do not know. Unfortunately, the trouble arose suddenly, and our force being small, it was impossible for us to make a lot of rapid determinations that would have been of great value to have on record. But if there are any here who can give me approximately what might be a quantitative value of the deterioration in these cables that I might expect in the future, I would be only too glad to receive it, or to be directed to any literature that may be printed on the subject. In this paper, reference is made to the maximum temperature at which the cable may be operated indefinitely without undue deterioration. Whether there is a time element involved there— presumably there is— I don't know. In our case for a period of at least 24 days, the temperature of certain portions of our cable was approximately 220 degrees Fahrenheit. In one instance where a steam service line crossed under a 10,000-volt lead-covered, varnished-cloth insulated cable, there was a failure—one of the crossings mentioned by Mr. Crawford. The cable was very old—one of the very early ones—and undoubtedly the breakdown was hastened by the excessive temperature. The 14,000 feet of cable that I am speaking of, however, is not high tension. It is single conductor used in the ordinary three-wire Edison system.

I wish to bring up the advisability of connecting with as strong a bond as possible, the neutrals of the system with the lead sheaths, so as to increase the carrying capacity of the neutral over and above the conductivity of the copper that is already in. In other words, to make the lead sheath act as a part of the neutral conductor. If there are any present who have followed out that system and have had any bad effects from it, I would like to hear from them. The author advises against this practise.

J. B. Fisken: In regard to the question Mr. Merwin asked as to using the lead sheath as part of the neutral conductor. I believe, where a street railway system is operated from the same power house as a d-c. distribution system using the same ground in the power house, it is impossible. A number of years ago, when we made the underground installation of our d-c. system in Spokane, we put in bare neutral conductors, and we found that with the variations on the street railroad load, the regulation of our lights was very bad. The investigation, of course, showed that the street railway current was coming back over the bare d-c. neutral and causing a very considerable drop. The result was that we had to take out all the bare neutral cables we had put in, and put in covered cables, and we had to keep our cables insulated to just the same degree as the outside wires.

S. C. Lindsay: We connect the neutral of the Edison system to the negative bus of the railway system where both systems are supplied from one station, but do not ground the Edison neutral at any other point. We also bond all the lead-covered cables together in each manhole and connect them to the negative bus of the railway system at the station, and have had no trouble from electrolysis on the cable sheaths during 13-years experience with this system of connections.

Referring to another part of Mr. Powell's paper, he says that the temperature of the duct lines should be taken midway between manholes. I am interested to learn of the method he used to obtain temperatures at those points. Further along in his paper, where he gives the rating of cables and loads to be placed on them at different temperatures, it seems to me that Mr. Powell's investigations do not enable us to load our cables any heavier than, nor quite as heavy as, some of the accepted methods of loading that we have been using. We have been loading our cables for a number of years heavier than any of the figures given by Mr. Powell, and we have been singularly free from cable troubles.

C. R. Collins: The author of this paper makes the statement in connection with the cables in duct lines: "The problem may conveniently be divided into two parts: viz., one having to do with heat transference from the air in the ducts to the earth directly in contact with the conduit, and the other with transference from the earth to the air at the surface." I do not see that he has taken into consideration the fact that a duct might be hotter at the center of the duct line than it would be near the edge. If we had some means of keeping the outside of a duct line cool, having it in contact with water for instance, the cable in the center duct would get much hotter than those in the outside ducts.

H. W. Buck: We had considerable experience at Niagara Falls in transmitting large amounts of current over large single-conductor cables, at 25 cycles. Our experience was in line with the paper, as to the serious amount of heating due to the induced current in the lead sheath. A one-million circular mil cable with an ordinary lead sheath carries 800 or 900 amperes. If the lead sheaths are short-circuited as secondaries to the copper, by connection together at the man-holes, the loss in the lead sheaths from induced currents is approximately equal to the copper loss. The question naturally arose as to whether these lead sheath currents could be stopped by breaking the connection between the lead sheaths. It could easily be stopped, but when the short-circuited connections were removed the induced voltages in the lead sheaths rose in some cases to as high as 500 volts. On this account we found that the damage due to the possible short-circuiting of these lead sheaths with an arcing contact, was a more serious matter than the power loss due to the current in the lead sheaths.

We also found, as referred to by the last speaker, that the temperatures, on the inside ducts of a group of ducts, might at times rise to a very high degree. Heat insulation of a nest of ducts is almost perfect to the inner ducts. We were obliged to abandon entirely all groupings of ducts more than two in width, so that the ducts would always have at least one side in contact with the earth. We made a number of tests on the heating of conduits, and found wide variations due to the seasons, and due to the character of the surrounding soil. When a new duct line was built, it did for a while operate at a low temperature. It would then gradually bake the moisture out of the surrounding earth, until the earth became a dry powder, and then the temperature would rise to a very much higher point. These wide variations in temperature, due to fluctuating conditions, should make engineers extremely cautious in estimating maximum temperatures, because the factors which enter vary within such wide limits.

Transmission of large alternating currents through single-conductor lead-covered cables should be avoided as much as possible on account of the eddy current heating. Not only is the heating objectionable, but the current flowing through the joints at manholes seems to have a disintegrating effect.

J. B. Fisken: Might I ask whether that was an alternating current?

H. W. Buck: Yes; alternating current; and the higher the frequency, the higher the eddy current loss.

S. C. Lindsay: Was any attempt made to cool your ducts at Niagara by forcing air through them with fans?

H. W. Buck: We tried various methods, and the air cooling method worked, but it required such a very high pressure of air that the power required was prohibitive. In some cases, where it was necessary to operate ducts having a large number of cables in a group, such, for instance, as 6 by 6, or 12 by 12, we placed water pipes through every other duct and kept a stream of water flowing through them. That was the only method which we found satisfactory for cooling the ducts under certain conditions.

S. C. Lindsay: The conditions for the absorption of heat into the soil were rather poor? The formation there is principally rock.

H. W. Buck: Yes; some broken rock, and some sand and clay.

S. C. Lindsay: Here in Seattle where the ground is saturated with water most of the time, we have a different condition. However, we had one particularly hot place in our underground system where we installed a fan in a manhole and ran an 8 inch pipe from the man hole to a pole on the sidewalk, and extended the pipe about twenty feet up the pole, forcing the hot air through this pipe with a 3-h.p. induction motor. The fan has been installed about two years and we are getting results from it.

H. W. Buck: The difficulties at Niagara were due to the large currents involved. The eddy-current loss in the lead sheath increases as the square of the current in the copper. We found that the permissible loss per duct foot varied from a minimum of about 1 watt per duct foot to 5 watts per duct foot, depending upon the conditions for getting rid of the heat.

L. T. Merwin: May I ask, if it were applicable, why did you not merely flood the ducts with water, rather than run a water pipe through adjacent conductors, as I understand you did?

H. W. Buck: If the ducts had been flooded, the manholes would also have been flooded, and it was easier to control the water by isolating it in pipes, than by allowing it to flow freely through the ducts themselves. In other words, it was not quite such a sloppy job.

L. T. Merwin: Would not the manholes have stood flooding?

H. W. Buck: No, they could not have been drained in this particular case, because they were below the level of the canal.

C. R. Collins: We tried the plan mentioned by Mr. Merwin, and found the water had disappeared before it got to the next manhole. A duct line will not always hold water.

H. W. Buck: That is true.

R. Howes: I would like to ask if any of you have had any experience with single-conductor cable on three-phase circuits under water, so as to state whether there is any electrolysis between the lead-covered cables?

H. W. Buck: Personally, I cannot answer that question from my own experience.

L. T. Merwin: Were these cables, lead cables?

H. W. Buck: Paper and rubber, both. Mostly paper.

L. T. Merwin Have you any means of knowing what limit of temperature was reached and for what duration, and could you place a value on the deterioration that took place in the insulation?

H. W. Buck: The temperature rose in some cases so high that the paper insulation was entirely carbonized.

J. B. Fisken: In reference to the remark made by Mr. Lindsay as to taking temperatures in the duct lines. I don't know whether this practise is followed or not, but it seems to me that in installing a large duct line, it would be good policy to leave a space vacant in the center. We have taken temperatures in our duct lines, not necessarily in the center of the duct line, but in other parts, by simply pulling in a registering thermometer, and leaving it there, for a certain time, and then pulling it out and reading it. I believe the heat in the center duct will be as great as in any in that duct line, especially if the ends were closed to permit the accumulation of heat in the duct. And then, by putting in the thermometer, we could make a thermal survey of that duct line, and tell very closely what the temperatures were.

H. W. Buck: I think that could be done very effectually, but it should be remembered that the temperature of the duct is not a correct indication of the temperature of the copper inside of the cables. The temperature gradient must be steep in order to force the heat out; consequently duct temperatures are very much lower than temperatures to which the cable insulation is subjected.

M. E. Cheney: In this capacity, I would suggest exploring coils in the center of the conduit lines, midway between the two manholes. You can determine the temperature in the cable by the difference in the resistance. That system is used a great deal in taking temperatures.

H. W. Buck: That method was adopted by Mr. Fisher in the tests referred to in this paper. All the temperatures were obtained by moving exploring coils along through the various ducts.

W. A. Del Mar: There are two conditions which Mr. Powell has not considered in his paper, which have an important bearing upon the carrying capacity of cables in ducts, namely: the influence of neighboring ca blesin reducing the continuous and short-time rating and the influence of the thermal capacity of the ducts in increasing the short-time rating. These are matters of the utmost importance but unfortunately experimental data are lacking. In the absence of such data the following suggestions are offered for discussion.

The influence of the number of similarly loaded cables in a conduit line may be estimated as follows, assuming the number of ducts to always equal the number of cables. Assuming a given temperature rise in the cable, let

n = Number of outside duct faces in the cross-section of conduit line.
N = Number of cables in the conduit line.
d = Heat dissipation per duct face per foot.
D = Heat dissipated per cable, per foot.
I_N = Current per cable with N cables similarly loaded.

I_1 = Current with one cable in a one-duct conduit line.
r = Resistance of cable, per foot, at ultimate temperature.

Then,

$$DN = dn$$

or,

$$D = \frac{dn}{N} \qquad (1)$$

By Joule's law,

$$I_N = \sqrt{\frac{D}{r}}; \qquad (2)$$

when the cable has reached its ultimate temperature.

Combining equation (1) and (2),

$$I_N = \sqrt{\frac{d}{r}} \quad \sqrt{\frac{n}{N}} \qquad (3)$$

And,

$$I_1 = \sqrt{\frac{d}{r}} \quad \sqrt{4} \qquad (4)$$

$$\therefore \frac{I_N}{I_1} = \sqrt{\frac{n}{4N}} \qquad (5)$$

Thus in the case of twelve similarly loaded cables in twelve ducts arranged 3x4, $N = 12$, and $n = 14$ and therefore by equation five,

$$\frac{I_N}{I_1} = \sqrt{\frac{14}{48}} = 0.54$$

Hence, due to the neighboring cables, each cable will carry continuously only 54 per cent of what it would carry if alone.

Table I shows the estimated influence of the heat storage capacity of tile ducts upon the short-time rating of a two-circular inch cable. The temperature rise of the duct is purposely underestimated.

TABLE I.

	Weight lb-ft.	Specific heat	Watt-hours per deg. cent.	Temp. rise deg. cent.	Total watt hr. absorbed
Copper	6.18	0.094	0.31	74	23
Insulation	0.97	0.360	0.18	72	13
Lead	4.54	0.031	0.074	69	5
Duct	11.00	0.200	1.16	25	29
					Total 70

The effect of the tile duct, in this case, is to add at least 70 per cent to the effective thermal capacity of the 2-cir. in. cable, and this proportion would be greater with smaller cables. In the case of a 2-cir. in. cable, the two-hour rating would be increased at least 20 per cent due to the thermal capacity of the duct.

A table of reduction factors for rectangular duct groups is given in Table II. These factors, being based upon the assumption that all the heat generated in the cables is dissipated into the earth through the duct walls, are incorrect for short-time ratings. If the absorption of heat by cables and ducts be taken into account, the reduction factors will approach unity, the shorter the rating period. Thus, the one-minute rating of a cable would scarcely be affected by the number of adjacent similarly loaded cables, as practically all the heat generated would be absorbed by the cable and duct. The two-hour rating, on the other hand, depends more upon the heat dissipation than upon the heat absorption and the reduction factors may be used with it, without great error.

Hence, the ratings in Table II are derived by calculating the two-hour rating for one cable in a duct, taking into account the thermal capacity of the cable and duct, and then multiplying by the duct reduction factors. The error, due to the assumption that these factors are correct for the two-hour rating, will not be very great and will be on the safe side. The ratings thus obtained are considerably in excess of those usually published, in spite of the low reduction factor and low temperature rise (25 deg. cent.) assumed for the ducts. Experimental data to carefully confirm this table, are lacking, but several observations upon cables in large groups, indicate that the ratings given for sixteen ducts or more, are conservative.

TABLE II.

CARRYING CAPACITY FOR TWO HOURS.

Single conductor, 2 cir. in., 650 volts, paper-lead in ducts, (74deg. cent.)

Number of ducts	Factor	Amperes	Number of ducts	Factor	Amperes
1	1	2840	28	0.444	1260
2	0.845	2400	32	0.433	1230
3	0.82	2330	36	0.425	1210
4	0.79	2240	40	0.416	1180
6	0.678	1930	44	0.412	1170
8	0.611	1740	48	0.408	1160
12	0.540	1530	52	0.404	1150
16	0.500	1420	56	0.401	1140
20	0.474	1350	60	0.398	1130
24	0.456	1300	64	0.395	1120

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INDUCTIVE INTERFERENCE AS A PRACTICAL PROBLEM

BY A. H. GRISWOLD AND R. W. MASTICK

Abstract of Paper

In this paper are given a review of the factors which affect inductive interference in telephone circuits from high-voltage power transmission circuits, a presentation of the practical considerations regarding the reduction of the interference, and a description of actual cases of the application of these means of reduction.

Distinction is made between the effect of balanced and of residual voltages and currents on the power circuit and between the effect of voltages induced between the wires and those induced between wires and ground.

The wave shapes of the voltages and currents in the power circuits have a very important effect in the amount of inductive interference in telephone circuits. The precision of the electrical balance of the power circuit is also important because of the relatively very large effects of unbalanced voltages and currents in producing inductive interference.

A discussion is given of the principles to be used in the design of coordinated transposition schemes for power circuits and telephone circuits which parallel each other, and schemes are described which have been devised for application to the telephone circuits in order to simplify the design of transpositions in the power circuits which make it possible to balance the induced voltages.

A detailed discussion is given of three particular cases of parallels showing the application to them of the different methods by which inductive interference can be reduced. In the appendix is an outline of information regarding parallels intended to facilitate the determination of the remedial measures desirable in any given case for reducing inductive interference.

THE discussions of the subject of Inductive Interference hitherto presented before the Institute and in the technical press, have dealt chiefly with the technical aspects of the problem. Very little has been said to show how the conclusions theoretically and experimentally established can be practically and successfully employed for the solution of problems in the field. It is the purpose of this paper to review some of the important aspects of inductive interference and to indicate by means of concrete examples, the solution of some of the practical problems met in the field. It will be our endeavor to show the simplicity of remedial measures in general in an effort to correct the idea prevalent among those who have not had time to carefully study the problem, that the measures developed to date are impracticable and burdensome.

Before proceeding to the discussion of remedial measures and their application, we believe it well to again review briefly, the factors involved, through which inductive interference arises. An understanding of these factors, and their relative importance, is necessary in order to appreciate the significance of the remedial measures.

In what follows, three-phase three-wire power circuits and metallic telephone circuits, physical or phantom, are assumed. We are concerned with voltages induced in the telephone circuit through two phenomena—electric and magnetic induction. Both effects are always present, and they combine to produce the resultant disturbance noted.

The voltage induced in the telephone circuit electrically and magnetically can be classified as:

1. Between the two sides of the circuit (referred to throughout this paper as the transverse effect).
2. Between the two sides of the circuit and ground, or along the circuit (referred to throughout this paper as the longitudinal effect).

The transverse induced voltages regulating through line impedances cause currents in the terminal apparatus. The longitudinal induced voltages, in addition to raising the telephone circuit to a potential with respect to earth which may be dangerous, cause currents in the telephone circuit owing to the differences in series impedances and admittances to ground of the two sides of the circuit.

A perfectly balanced power or telephone circuit may be defined as one in which the series impedances of the several phases and the admittances between the several phases and ground are exactly the same at every point.

If it were possible to construct a perfectly balanced telephone circuit, there could be theoretically no transverse induced voltage, regardless of the magnitude of longitudinal induced voltage provided that a sufficiently large number of exactly spaced transpositions were placed in it so as to equalize the induced voltages in each side.

Conversely, if it were possible to construct a perfectly balanced power circuit, there could be theoretically no voltages induced on a parallel telephone circuit, provided that a sufficiently large number of exactly spaced transpositions were placed in it so as to expose each phase of the power line equally to the telephone line.

In practise, the balance of neither power nor telephone circuits can be made perfect as defined above, and it is, therefore, necessary, in order to avoid induction into paralleled telephone circuits, to balance both power and telephone circuits as well as practicable, and also transpose both circuits with due regard to one another.

It is convenient to consider the voltages and currents in the power circuits, which cause induction, as consisting of two components:

1. Balanced voltages and currents.
2. Residual voltages and currents.

The balanced components are three voltages or currents equal in magnitude, displaced 120 degrees in time-phase with respect to one another, and whose vector sum is, therefore, zero.

Single-phase loads connected between wires cause voltage and current components whose effects are very similar to those of balanced three-phase voltages and currents, and are treated in a like manner.

The residual components are three voltages or currents equal in magnitude, in common time-phase, and whose vector sum is, therefore, not zero.*

The balanced voltages and currents are those which perform the useful functions of the power system. On the other hand, it is significant and fortunate that the residual voltages and currents are not essential to the operation of the power system.

Balanced voltages and currents are common to either of the two general types of power systems (grounded or isolated), and the remedial measures for the mitigation of inductive effects arising therefrom are identical. This is not true of the residual voltages and currents. These arise from different sources in the two types of power systems, and generally exhibit characteristics peculiar to the particular type of system.

The remedial measures for their mitigation are also distinctly different.

Thus, it will be seen that there are two different phases of the general problem of inductive interference, *i.e.*,

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*See Appendix II, Report of Joint Committee on Inductive Interference. A. I. E. E. TRANSACTIONS, Volume XXXIII, p. 1461.

1. The mitigation of induction arising from the balanced voltages and currents, requiring remedial measures which are the same whether the power system be isolated or grounded.

2. The mitigation of residual voltages and currents requiring remedial measures peculiar to the particular type of power system involved.

Residual voltages and currents may arise in different types of power systems from one or more sources which act singly or together.

On grounded systems, the principal sources of residual voltages and currents are:

1. Unbalanced loads between the three-phases and neutral, causing unbalanced-load currents to flow through the neutral to earth.

2. The third harmonic and its odd multiples, due to a variation of permeability of the iron, occur in common time-phase in the three phases of the transformer banks, thus giving rise to a residual component of voltage and current in the connected transmission lines.

On systems isolated from ground, the principal source of residual voltages and currents is:

Unbalanced capacitance and conductance between the several phases and ground. The conductance factor is generally of minor importance on well constructed and maintained systems.

The tendency in the best power system design and operation is inherently toward practises which reduce the possibility of large residuals. Moreover, the majority of the future parallels with communication circuits will undoubtedly be short, owing to the increasing tendency of both power and telephone companies to seek private rights-of-way. Were this not so, the problem of mitigation of residuals would be as difficult to combat in the future as it is at present. With the increased attention being devoted to this matter we expect that the longitudinal effects of residual voltages and currents will, in the shorter parallels, be reduced to magnitudes small enough to be relatively unimportant.

It must be realized that the inductive effect per volt or ampere of residual voltage or current is proportionately far greater than for equal amounts of balanced voltage or current. It should be clearly understood that the mitigation of residuals where parallels of considerable length are involved is of great importance. The longitudinal effect then becomes of importance by maintaining the telephone circuit as a whole above ground potential and producing a transverse effect by virtue of the unbalances inherent to commercial circuits.

The wave forms have much to do with the severity of induction. Higher harmonics are present in both voltages and currents and their power of producing disturbances increases with very great rapidity up to about 800 cycles. Practically all noise in telephone circuits caused by induction from power circuits arises from the higher harmonic voltages and currents. Were these entirely absent, the problem of inductive interference would be indeed simple of solution, for then we should have to deal with only the fundamental frequency which is scarcely audible to the human ear.

The frequency and magnitude of these attendant harmonics should determine the extent of remedial measures to be applied owing to the variation in effectiveness of given remedial measures and severity of induction with the frequency.

Another important phase of the problem is the question of abnormal conditions, accidental or otherwise, on the power system. An abnormal condition in any type of power system, whether it be due to an accidental ground, short circuit, open-circuit or switching operation, produces a great increase in the residual voltage or current, or both, of the system momentarily, or for a considerable period of time, as the case may be.

On a star-connected grounded-neutral system, an abnormal condition generally produces a large residual current which is approximately equal to the short-circuit current to ground (if the condition be one of a grounded phase) on that portion of the circuit between the sources of power supplying the fault and the point where the fault occurs, or if the fault be an open one in phase, the residual current will equal the unbalanced-load currents flowing in the other two phases. A residual voltage is created in proximity to the fault and in certain instances throughout the length of the circuit from the fault to the receiving transformers, which voltage approaches as a maximum 58 per cent of the voltage between phases.

On an isolated system, a ground on one phase causes a large residual voltage throughout the entire length of the circuit whose magnitude is 173 per cent of the voltage between phases. A residual current is created in proximity to the fault, its magnitude depending upon the extent, voltage and frequency of the system.

Fortunately, abnormal conditions are becoming less frequent, owing to the demand for greater continuity of service, leading to better construction of power lines and to the use of better apparatus. There have been no remedial measures developed which can adequately care for the inductive disturbances attendant to abnormal conditions of power lines, nor are such expected.

It is, therefore, a question of reducing to a minimum the accidents on the power lines by proper construction and maintenance and of using methods and apparatus in switching which shall incur the least possible disturbances.

The difficulties encountered in attempting to mitigate the disturbances under abnormal power circuit conditions constitute an additional reason why it is very desirable to avoid parallelism wherever possible.

As an instance in which the use of improved methods and apparatus have resulted in a material reduction of transient disturbances, the charging of electrolytic lightning arresters can be cited. Since the adoption of the four-tank electrolytic lightning arrester, the use of charging resistances and metallic contact during charging, the formerly serious transient disturbances experienced on parallel telephone lines at times of charging, have been largely reduced.

The configuration and spacing of the power-circuit conductors has an important bearing on:

1. The liability to short-circuits on the line.
2. The residual voltage (of an isolated system).
3. The resultant induction from balanced components.

Since the last two items can be cared for by transposition, the first is of chief importance.

Vertical configuration of a power circuit renders it liable to short-circuits where snow and sleet are encountered.

The equilateral triangle is far superior to either vertical or flat construction with respect to residual voltage caused by capacitance unbalance. The wishbone configuration is intermediate. For induction from balanced components, the differences are less marked, the flat configuration causing the most induction.

The configuration of telephone circuits is standardized to a far greater degree, and since transposition is comparatively inexpensive and effective, the configuration of telephone circuits is relatively unimportant with regard to the mitigation of induction.

For the mitigation of inductive effects produced by the balanced voltages and currents, transpositions offer the most feasible, simple and effective means developed to date. A transposition in a circuit interchanges the positions occupied by its conductors. In a three-phase power circuit, a transposition changes the phase of the induction produced by the balanced voltages and currents by 120 degrees. Thus, by locating power-circuit transpositions so that each conductor occupies all of the several conductor positions for equal distances, a "barrel" is obtained within which the vector sum of the induced voltages on an untransposed parallel circuit is zero. The effect of transposing a power circuit may, therefore, be said to be one of neutralization.

A transposition in a telephone circuit changes the phase of the induced transverse voltage by 180 degrees, that is, it reverses in successive lengths the phase of the induction between the two sides of the circuit. Transposition of a telephone circuit, therefore, exposes each side of the circuit equally to the influence of the power circuit, and the effect may be said to be one of equalization. It should be noted that the phase of the longitudinally induced voltage is in no wise changed by transpositions in the telephone circuit.

This change of phase of the induction into a telephone circuit by transposition in either the power or telephone circuit, or both, affords a means of reducing inductive effects in that the induction in one section may be largely neutralized by the induction in neighboring sections.

A proper adjustment of neutralization and equalization effects by transpositions in both power and telephone circuits constitutes a "co-ordinated transposition scheme" as referred to throughout the remainder of this paper.

In Fig. 1 is shown a co-ordinated transposition scheme in the case of a three-phase power circuit and a simple metallic telephone circuit. Let the three configurations of the power circuit be designated A, B, C. Let a and a' denote the length of telephone circuit, exposed to configuration A; b, b' and c, c' are similarly defined. Primes denote that there is an odd number of telephone transpositions between the given length and the reference section of the telephone conductor. For balance to induction the lengths a, a', b, b', c, c' must fulfill the relation

$$\Sigma a = \Sigma a' = \Sigma b = \Sigma b' = \Sigma c = \Sigma c'$$

Longitudinal induction balance for balanced voltages and currents is obtained when the condition

$$\Sigma\,(a + a') = \Sigma\,(b + b') = \Sigma\,(c + c')$$

is fulfilled.

Transverse induction balance for balanced voltages and currents is obtained when the condition

$$\Sigma\,(a - a') = \Sigma\,(b - b') = \Sigma\,(c - c')$$

is fulfilled.

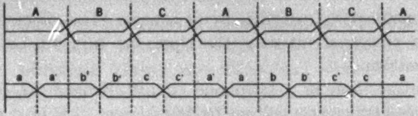


Fig. 1.

The system of "barreling" shown in Fig. 1 is called "continuous barrelling." In practise where long uniform parallels occur, it is possible and many times desirable to modify the co-ordinated system shown in Fig. 1 by omitting every third power transposition as depicted in Fig. 2, thus obtaining a system of "non-continuous barrelling."

The same conditions for balance hold for this system as given for continuous barrelling shown in Fig. 1. The only advantage of continuous barrelling over non-continuous is that balance is obtained in any three consecutive sections regardless of the point of starting.

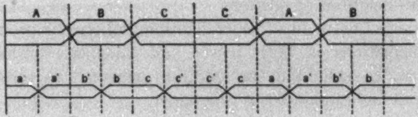


Fig. 2.

Power circuit transpositions with reversed rotation are sometimes used when it is necessary to obtain an exposure of a particular phase in a particular section to balance with another type exposure in some other section of the parallel. A simple illustration is shown in Fig. 3.

It is interesting to note that the use of reversed power transpositions in the manner shown also results in not altering the relation of power wires at ends of the parallel. Reversing the rotation of a power circuit transposition changes the phase of the induction in the section of parallel immediately beyond the transposition by 240 degrees. Since a telephone transposition changes the phase of the induced voltage by 180 degrees, it is obviously immaterial whether the rotation of telephone transpositions be normal or reversed. Normal rotation is considered as that of the existing transpositions in a given power line.

Transpositions of the power circuit in no way changes the phase or magnitude of induction produced in telephone circuits by residual voltages and currents, except in so far as it changes the residual voltages and currents themselves, which happens in some cases.

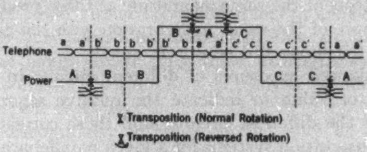

Telephone
Power
a
a'
b'
b
b
b'
b'
b
a
a'
c'
c
c
c'
c'
c
a
a'
B
A
C
A
B
B
C
C
A
Transposition (Normal Rotation)
Transposition (Reversed Rotation)

FIG. 3

Longitudinal induction from the residual voltages and currents cannot be reduced by either power or telephone transpositions. It follows, therefore, that the reduction or elimination of longitudinal induction from residual voltages and currents must come about through a reduction or elimination of the residuals themselves in the power system.

Transposition of the telephone circuit is an effective means for reducing the transverse induced voltage produced by residual voltages and currents.

Transverse balance for induction from residual voltages and currents is obtained when the condition (see Figs. 1, 2, or 3).

$$\Sigma\,(a + b + c) = \Sigma(a' + b' + c')$$

is fulfilled.

When the conditions for balance cited above are not fulfilled the unbalanced exposures are as follows:

TABLE I.

Type of Induction	Component of power circuit voltage or current	Length of unbalanced exposure
Transverse	Balanced	$\Sigma(a-a')\underline{/0^\circ}+\Sigma(b-b')\underline{/120^\circ}+\Sigma(c-c')\underline{/240^\circ}$
"	Residual	$\Sigma(a+b+c)-\Sigma(a'+b'+c')$
Longitudinal	Balanced	$\Sigma(a+a')\underline{/0^\circ}+\Sigma(b+b')\underline{/120^\circ}+\Sigma(c+c')\underline{/240^\circ}$
"	Residual*	$\Sigma(a+b+c+a'+b'+c')$

*Independent of all transpositions.

The "unbalanced exposure" is the length of exposure between untransposed telephone and power circuits which will produce inductive effects of the same magnitude as those produced in the actual exposure of the same configuration with the given transpositions in telephone and power circuits.

The unbalanced exposures of different circuits in any given parallel are of value to indicate the relative severity of the induction in the different circuits, and those corresponding to different transposition systems for a given parallel are indicative of the relative effectiveness of such transposition systems.

Summing up from the discussion above; the various factors involved and the conditions for induction balance between power and telephone circuits may be simply tabulated as follows:

TABLE II.

Type of induction	Component of power circuit voltage or current	Condition for balance	Balance depends on transpositions in
Transverse	Balanced	$\Sigma(a-a')=\Sigma(b-b')=\Sigma(c-c')$	Both lines
"	Residual	$\Sigma(a+b+c)=\Sigma(a'+b'+c')$	Telephone line
Longitudinal	Balanced	$\Sigma(a+a')=\Sigma(b+b')=\Sigma(c+c')$	Power line
"	Residual	—	—

The application of telephone transpositions in a manner to obtain the conditions for balance indicated in Table II is subject in practise to the condition that on telephone leads carrying more than one circuit, it is necessary to provide against induction from one telephone circuit into another, commonly referred to as "crosstalk". This necessitates a complicated telephone transposition system to provide balance for induction from outside sources such as power lines and also among all the circuits on the telephone lead.

Even though it were possible in practise to fulfill exactly the conditions for balance as indicated in Table II, there would still be present some inductive effect because of the changes in phase and magnitude of the voltages and currents along the power line. This point has an important bearing on the length of the power-circuit barrel, for it is necessary in order that this effect be rendered sufficiently small, that the conditions for balance outlined in Table II be fulfilled within as short a length of exposure as is practicable. In practise, it has been found, in some cases, that barrels in the power circuit six miles in length are satisfactory. Except under very severe exposure conditions we believe that barrels in the power circuit three miles in length will afford a satisfactory solution when uniform sections of parallel are long enough to permit their use.

Points of discontinuity within a parallel, such as changes in configuration of either power or telephone circuit, large changes in the separation of the two lines, crossovers, branch loads, loading points in the telephone line, or in fact any points at which an abrupt change in magnitude or phase of the power line voltages or currents or induced voltages occurs, should in general be made neutral points. In other words, balance to induction should be obtained between such points of discontinuity independently of the remainder of the parallel. Thus the number of and distance between points of discontinuity is a controlling factor in determining the length of power-circuit barrel. It should be noted in this connection that a loading coil in the telephone circuit is a discontinuity with respect to the transverse induced voltage, but not with respect to the longitudinal induced voltage, since the loading coils are non-inductively connected in the circuit formed by the telephone wires and ground.

Crossovers of power and telephone lines within the parallel are in general considered as points of discontinuity. In some cases, however, where the same separation obtains between the power and telephone lines before and after crossover, it is possible by interchange of the pin positions of the power wires to make the crossover equivalent to a transposition in the telephone circuit, or in both the power and telephone circuits. If the crossover is treated in such a manner, it need not be considered as a point of discontinuity.

In Fig. 4 are shown several types of crossover transpositions represented by the terms "0° crossover", "120° crossover" and "240° crossover" which number of degrees has reference to the change in phase of the longitudinal induced voltage between the two sections immediately adjacent to the crossover.

It has been previously pointed out that transposition of the telephone circuit is an effective remedy for reducing the transverse induction from residual voltages and currents; that longitudinal induction from the same source cannot be cared for by either power or telephone transpositions, hence must be reduced by a reduction of the residual voltages and currents within the power system.

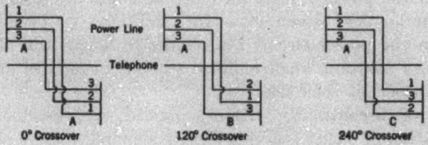


Fig. 4.

In the type of power system isolated from ground, the problem of reducing residual voltages and currents is a comparatively simple one. Earlier herein it was stated that the principal source of residual voltage and current in systems isolated from ground is the unbalanced capacitance between the several wires of the circuit and ground. Hence the remedial measure obviously necessary is a balancing of these capacitances to ground. This is most readily accomplished by transposing the power line throughout its extent (including all the lines metallically connected to the one in the parallel) so that each conductor occupies the several pin-positions for equal distances.

To a company operating an isolated system of large extent, this remedy appears to be a severe and costly measure, unless very few and widely separated transpositions will accomplish the desired result. In general, practise indicates that transpositions for this purpose can be relatively few and widely separated. Here again in determining the length of barrel required, the wave-shape of the residual voltage is a dominant factor, since with the higher frequencies shorter barrels are necessary.

It does not seem probable that barrels of less than 6 miles in length will generally be required and in some cases longer barrels will be sufficient. Branch lines, switching points and changes of configuration must be taken into account and frequently fix the length of barrel.

In the construction of new lines, it is a very simple and inexpensive matter to cut in transpositions at reasonable distances to accomplish the reduction of residual voltage without detriment to the operation of the system. Then if parallelism occurs in the future, the only transpositions required would be in and near the parallel.

With existing parallels, it may or may not be necessary to transpose the power line outside the parallel, depending upon the severity of the exposure. In any event, all of the measures should be applied within the parallel and found insufficient before giving consideration to this point.

In the type of power system operated with a star connection of transformers and grounded neutral, the reduction of residual voltages and currents is not so readily accomplished as in the case of systems isolated from ground. Two principal sources of residual voltages and currents for this type of system have been previously mentioned herein; namely, unbalanced loads between the three-phases and neutral, and the introduction of the third harmonic and its odd multiples as residuals.

The obvious measure against the former is the removal of all grounded neutrals but one, thus removing the ground path for the unbalanced currents. In some cases this may not always be considered safe or feasible, particularly if the network be of large extent. There seems to be, however, a growing tendency on the part of power companies operating systems of large extent toward the elimination of the ground connection at all but important generating and switching points. Since the use of grounded single-phase loads has almost disappeared from practise with the larger power companies, it is now generally true that power circuits operated by such companies can be very well balanced as to magnitude of load current in the three phases and the unbalanced load current can usually be practically eliminated.

The introduction of the triple harmonics as residual voltages and currents is the chief problem of the grounded neutral system. Since these triple-harmonic voltages and currents are introduced through the effect of variable permeability of iron in transformers and as their magnitude is directly dependent upon the magnetic density at which the transformer is operated, this type of residual is reduced by operating the transformers below their rated voltage. There is no doubt that the practise of operating transformers over rated voltage is the cause for the large residual current of triple frequencies observed on star-connected systems, since the magnitude of these harmonics increases very rapidly as the transformer iron approaches magnetic saturation.

The employment of the delta-star connection of transformers on grounded systems is greatly preferable to the star-star connection, in that the delta winding provides a low impedance path for the triple harmonics, in parallel with the path provided by the line and earth, hence reduces the magnitude of such currents over the line and earth path.

It is difficult to accurately predict on systems employing the star-delta type of connections whether or not the magnitude of triple harmonic residual will be large enough to cause severe inductive effects, since it depends upon a multitude of considerations dealing with the interaction of different portions of the system on one another.

In the case where both star-star and star-delta banks are used, the line sides being in star with grounded neutral, the star-delta bank offers a low-impedance path for the triple-harmonic magnetizing currents of the star-star bank. Hence in the line, between two such different banks, there will be a large residual current, and an exposure occurring there is liable to serious induction. Such a star-delta bank may, however, be used as a shunt path for the triple-harmonic residuals, and greatly reduce their magnitude in the line beyond. Thus, a remedial measure is suggested for the mitigation of triple-harmonic residuals on systems employing the star-star connection.

The triple-harmonic circulating current of the delta winding is greatly increased where such connection is used in combination with star-star banks and hence a star-delta bank of size comparable with the star-star bank is required to give effective results.

On a system employing only the star-star connection of transformers with grounded neutrals, it is always a safe prediction that serious triple-harmonic residuals will be present, and it is essential that measures for their reduction be considered. Tertiary delta windings on such transformers are beneficial and new transformers for proposed installations of this connection should be designed to provide such windings. Power engineers recognize the advisability of providing such windings for their own benefit when using this type of connection so that much of the trouble formerly experienced will thereby be eliminated in the future.

The interconnected-star is a method of reducing triple-harmonic residuals by neutralization. Besides being less efficient than the star-delta connection, it reduces the voltage rating by 13 per cent and requires a more complicated arrangement of the wiring.

It will be seen from the above discussion of the mitigation of residual voltages and currents under normal operating conditions, that:

1. In isolated delta-connected systems, residuals may be effectively and easily reduced by simple means.
2. In star-connected grounded systems, several measures can be practised for reducing residuals all of which will reduce them with some degree of success but none of which are entirely satisfactory.

Types of power-circuit transpositions and barreling have been described previously and their application to the practical case will be readily understood. In the case of telephone transpositions, only a single metallic circuit has been considered in the discussion of the co-ordination of transpositions, without reference to cases where more than one telephone circuit is involved other than to mention the fact that the problem was further complicated.

For the application of co-ordinated systems of power and telephone transpositions to the practical case, a telephone transposition system has been designed which will care for as many as forty telephone wires (20 physical and 10 phantom circuits), providing adequate crosstalk balance between the telephone circuits themselves and being capable of properly co-ordinating with power-circuit barrels of varying lengths. Further work is in progress which will extend this system to a full eighty-wire lead.

This system is known as the "exposed line system". It is comprised of two types of sections as follows:

1. Exposed line *A* section.
2. Exposed line *X* section.

Additional short sections, whose characteristics have not, as yet, been determined, are in the process of development; namely, the exposed line *Y* and *Z* sections.

The exposed line *A* section is nominally eight miles in length with 32 transposition points for the circuits most commonly used, and has been designed to give high crosstalk-balance together with induction balance to power lines transposed:

1. Opposite any mile-points of the telephone transposition system.

2. With two complete barrels (five transpositions of the power line) between mile-points of the telephone transposition system.

Thus, for a uniform parallel, this section gives balance to induction from power lines transposed with six-mile, three-mile or one-half mile barrels. It is possible to adjust the length of this nominal eight-mile section to any value less than eight miles, and this is frequently done in adjusting the sections or mile-points to correspond with discontinuities in the parallel. Transverse balance of all circuits to induction is accomplished in every mile.

The exposed line *X* section is nominally one-half mile in length with four transposition points, and is so designed that any number of units may be installed end to end. The *X* section unit does not balance to power lines transposed within any one unit, but is designed to be so used that transpositions of the power line and discontinuties of the exposure occur at junction points between successive units. Thus balance to induction is obtained in three successive sections if power transpositions are located opposite their junction points. Nominally this would give a power circuit barrel of one and one-half miles. The *X* section can be made of any length less than one-half mile per unit where required.

Short exposed line sections may be used in any part of an eight-mile loading section, and the remainder transposed according to some other transposition system.

By "other transposition systems," reference is made to the "standard system" which involves the use of four sections, *A*, *X*, *Y*, and *Z*, whose nominal lengths are 8, ½, 1½ and 4 miles respectively. In the standard system, however, balance to induction from outside sources, such as power lines, is not obtainable except by modification of certain of the transpositions involved. Also, the use of the *X*, *Y*, or *Z* sections consecutively is not permissible without modification.

Another method sometimes used is to superimpose on the crosstalk transposition systems, already in the line, special transpositions of all the telephone circuits on poles between the regular transpositions poles. That is, their function is to transpose all circuits with reference to outside circuits so as to give a minimum of disturbance to the crosstalk balance of the telephone circuits themselves. The prime purpose of "whole-line" transposition is, therefore, to make possible the retention of systems of transposition involved in parallelism which do not provide balance to induction in themselves. The use of whole-line transpositions is limited by crosstalk considerations to some extent where phantom or loaded circuits are involved. Their chief application is to very short parallelisms.

There are two types of whole-line transpositions; namely, the quarter-mile unit and half-mile unit. These are shown in Fig. 5.

The use of short sections or whole-line transpositions is deleterious to the telephone service in that it is impossible with these arrangements of transpositions to reduce cross-talk as effectively as with eight-mile sections. Moreover, the difficulty of maintenance of telephone service is increased.

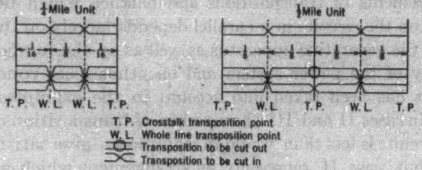

¼ Mile Unit
1/16
⅛
1/16
T. P.
W. L.
W. L.
T. P.
½ Mile Unit
⅛
⅛
⅛
⅛
T. P.
W. L.
T. P.
W. L.
T. P.
T. P. Crosstalk transposition point
W. L. Whole line transposition point
Transposition to be cut out
Transposition to be cut in

FIG. 5.

In order to illustrate in a more comprehensive manner the application of remedial measures, such as have been described and discussed in the previous sections of this paper, a few concrete examples will be cited and their solutions discussed. Before doing this, however, we believe it well to call attention to the fact that the successful design of remedial measures necessitates an exact knowledge, on the part of the engineer, of many details of the particular case. Not only must he be thoroughly conversant with the telephone circuits involved, but he must also be conversant with the characteristics of the power system involved. It is highly desirable that a personal inspection be made and copious notes taken in order that all practical difficulties be observed in advance of the design of remedial measures. That it is not possible for the engineer to personally inspect every case is recognized, hence the data must ofttimes be collected by some other person, and it is, therefore, necessary that a procedure be devised for presenting an accurate and detailed report to the engineer for his guidance.

Through the courtesy of The Pacific Telephone and Telegraph Company, we present in Appendix I of this paper the pertinent part of an engineering circular, describing a procedure for surveying a case of parallelism and for transmitting an accurate account of the essential facts, which we have found exceedingly satisfactory.

In the examples which follow, the symbolic representations described in Appendix I are used, and the reader is referred to this Appendix for their explanation.

The foregoing text has emphasized the fact that the severity of requirements of transpositions and balance which must be imposed on the circuits in a parallel depends largely on the wave shape of the generating apparatus as well as on the fundamental frequency of the power system and on other local conditions. This fact has been taken into account in the examples given below. In cases II and III the number of transpositions in the power circuits is less than would in many cases give satisfactory results, but case II represents an arrangement which was applied with success, and case III, one which it seems reasonable to install, in a particular case which has arisen.

CASE I

Case I presents an example of a uniform parallel involving three power circuits (see illustration) whose parallelism is coincident for a little over half of the total parallel. The case was presented for solution as a practical problem in the field, and the remedial measures to be described have been installed in part and found effective. The details of the parallel and characteristics of the power lines and telephone system are as follows:

Power Systems No. 1. 30,000 volts, three-phase, 50 cycles, vertical configuration; tower construction; star-star connected and star-delta connected transformer banks employing a ground connection. No transpositions.

No. 2. 15,000 volts, three-phase, 50 cycles. Flat configuration; pole construction; star-star connected transformer bank supply with grounded neutral and delta-delta and star-star (isolated neutrals) connected load banks. No transpositions.

No. 3. 15,000 volts, three-phase, 50 cycles. Triangular configuration; pole construction; star-star connected transformer bank supply with grounded neutral and delta-delta connected load banks. No transpositions.

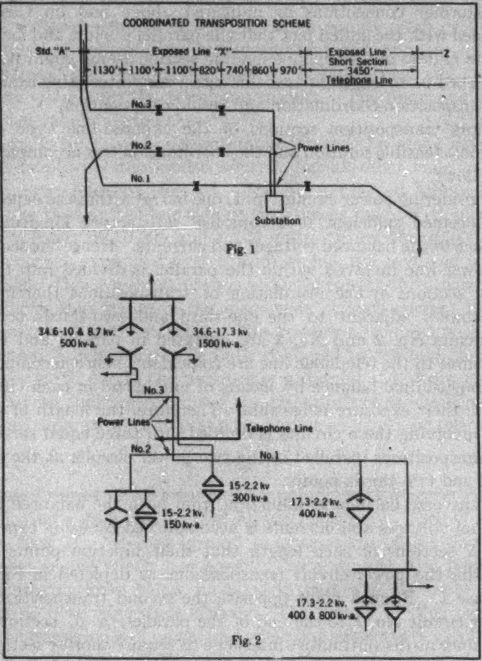

COORDINATED TRANSPOSITION SCHEME
Std. "A"
Exposed Line "X"
Exposed Line Short Section
Z
1130'
1100'
1100'
820'
740'
860'
970'
3450'
Telephone Line
No. 3
No. 2
No. 1
Power Lines
Substation
34.6-10 & 8.7 kv. 500 kv-a.
34.6-17.3 kv 1500 kv-a.
No. 3
Power Lines
Telephone Line
No. 2
No. 1
15-2.2 kv 300 kv-a
15-2.2 kv. 150 kv-a.
17.3-2.2 kv. 400 kv-a.
17.3-2.2 kv. 400 & 800 kv-a.

Fig. 1

Fig. 2

Case I.

Telephone System. High-grade loaded physical and phantom long distance circuits; ultimate capacity of lead 40 physical and 20 phantom circuits. Standard system of transpositions.

Parallel. 10,170 feet in length; separation of power and telephone leads: No. 1, 75 feet; No. 2, 49 feet; No. 3, 18 feet. Crossover at beginning of parallel circuits No. 1 and No. 3.

Co-ordinated Transposition Scheme. The variation in length of parallelism of the three power lines, different separations from the telephone line, difference in voltages, configuration and transformer connections as indicated above and on Case I, coupled with the added fact that the parallel is short and located in the middle of a telephone loading section which could not be disturbed as to length, makes this case a very interesting example of transposition-coordination and residual-mitigation.

Short transposition sections of the exposed-line type offer the most feasible solution and the coordination was accomplished as follows.

Considering power circuit No. 1, one barrel within the exposure was deemed sufficient to accomplish satisfactory longitudinal balance to the balanced voltages and currents. Hence the section of power line involved within the parallel is divided into three equal sections by the installation of transpositions therein at the towers adjacent to the one-third and two-thirds points.

Circuits No. 2 and No. 3 are operated in parallel and their exposures to the telephone line are coincident, hence accomplishing longitudinal balance by means of one barrel in each circuit within their exposure is feasible. Therefore, the length of parallel involving these circuits is divided into three equal sections by transpositions installed in the two power circuits at the one-third and two-thirds points.

Transverse balance to induction from both the balanced and residual voltages and currents is accomplished by using exposed line *X* sections of such length that their junction points fall opposite the power-circuit transpositions as depicted in Fig. 1 of Case I. From a point opposite the second transposition in power circuit No. 1 to the end of the parallel, a *Y* section is used since no discontinuities intervene to require shorter sections.

Mitigation of Residuals. The mitigation of residuals for this case brings out some interesting features. Considering Circuit No. 1 (see Fig. 2, Case I), a combination of star-star and star-delta connected transformer banks, with grounded neutrals is employed. As pointed out in a previous section of this paper, a condition is here established which is conducive to the passage of large triple-harmonic residual currents over the power line past the exposure with consequent heavy longitudinal induction on the telephone circuits. The obvious measure for reducing such effect was to remove the low-impedance path of such currents. Accordingly, it was suggested that the neutral on the low side of the star-star connected supply bank of transformers be ungrounded. This request was acceded to and the residual current was thereby reduced to a value small enough to have no appreciable inductive effect on the telephone circuits.

With the neutral of the No. 1 circuit supply bank grounded on the low-voltage side, some transient disturbances on the 60,000-volt line feeding the bank were transformed and caused severe trouble on the telephone circuits. The ungrounding of the neutral eliminated this trouble.

Circuits No. 2 and No. 3 are supplied from a star-star connected bank employing a grounded neutral, but all other transformers on the two lines are isolated. The star-connected supply bank has two taps on the low side so that power may be supplied at star voltages of 10,000 and 8,700 volts. From the 10,000-volt tap energy is supplied over a third circuit not involved in the parallel. Hence a shunt path is provided for the third-harmonic residuals, thus reducing the magnitude of such current in the line involved in the parallel. This condition, coupled with the fact that a high-impedance path is offered to residual currents via the earth due to the presence of a ground at but one end of the circuit, sufficiently reduces the magnitude of residual current in this short parallel so that its inductive effect can be tolerated.

CASE II

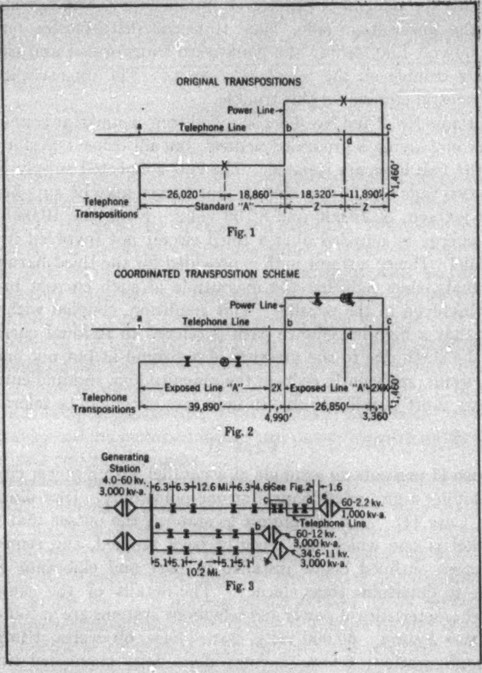
Case II presents an example of a parallel with a power circuit employing a grounded neutral at one point only. (See illustration, Case II). It is of interest to state at the outset that this parallel is one which has recently been studied, the remedial measures outlined below installed in part and elaborate tests made to determine their efficacy. The details of the parallel and characteristics of power and telephone systems are as follows:

Power System. 60,000 volts, three-phase, 60 cycles, triangular configuration; 6-foot spacing; delta-delta connected transformer banks throughout the system with one exception; a star-connected bank with grounded neutral at one end of the line (see Case II.) Three existing transpositions; two within parallel and one outside.

Telephone System. One long-distance telephone circuit and several long suburban circuits. Standard system of transpositions.

Parallel. 75,090 feet in length; separation between power and telephone leads, 45 feet. Two crossovers, one of which is at the end of the parallel.

Co-ordinated Transposition Scheme. In this case a long uniform parallel is presented which offers an excellent opportunity for the use of the exposed line *A* section.


ORIGINAL TRANSPOSITIONS
Power Line
Telephone Line
a
b
c
d
26,020'
18,860'
18,320'
11,890'
1,460'
Standard "A"
Z
Z
Telephone Transpositions
Fig. 1
COORDINATED TRANSPOSITION SCHEME
Power Line
Telephone Line
a
b
c
d
Exposed Line "A"
2X
Exposed Line "A"
2X
39,890'
4,990'
26,850'
3,360'
1,460'
Telephone Transpositions
Fig. 2
Generating Station
4.0-60 kv.
3,000 kv-a.
6.3
6.3
12.6 Mi.
6.3
4.6
See Fig. 2
1.6
a
b
c
d
e
60-2.2 kv.
1,000 kv-a.
Telephone Line
60-12 kv.
3,000 kv-a.
34.6-11 kv.
3,000 kv-a.
5.1
5.1
10.2 Mi.
5.1
5.1
Fig. 3

Case II.

The method was adopted of installing first a very small number of transpositions in the power circuit to determine the extent to which the induction was reduced. The design is such that additional power transpositions can be economically installed if later found desirable.

Referring to Fig. 2, Case II, beginning at point *a* (the commencement of parallelism) an exposed line *A* section is installed of such length that it occupies eight-ninths the total distance from point *a* to the crossover at point *b*. Thence, two *X* sections of equal length extend to the crossover point *b*. Transverse balance is obtained when the existing power transposition is removed. Longitudinal balance to induction from the balanced voltages and currents of the power system is accomplished by installing a barrel in the power circuit between points *a*, *b*, with two transpositions opposite the three-ninths and six-ninths points of the telephone transposition system.

From the crossover at point *b*, another exposed line *A* section is installed of such length that it occupies eight-ninths the total distance from point *b* to the end of the parallel at point *c*. Thence two *X* sections of equal lengths are installed, extending to the end of the parallel, at *c*.

Transverse balance is obtained when the existing power transposition in this section is removed. Longitudinal balance is obtained in the same manner as outlined for section *a*, *b*, but with reversed rotation of power transpositions, the purpose of which will be explained below.

Thus, coordination of the power and telephone systems is obtained within the parallel in so far as induction from balanced voltages and currents of the power system are concerned, and also transverse induction balance from the residual voltages and currents.

It will be noted by referring to Figs. 1 and 2 that a junction occurs in the telephone line at a point *d* which would ordinarily be treated as a point of discontinuity, and, therefore, balance to induction should be obtained on either side of it. In this case, such balance is unnecessary since the junction point shown represents a tap off the long distance circuit under consideration. Had one or more circuits branched from the lead or terminated at this point, the others running through, it would have been necessary to make the junction a neutral point and obtain balance independently on each side. This would probably have required the use of short sections in the telephone line and two additional transpositions in the power line.

Mitigation of Residuals. Due to the presence of the grounded-neutral bank at one station and the triangular configuration used in most of the system the effect of capacitance unbalance of the lines in causing residual voltage will be very small. Hence under the operating condition shown in Fig. 3 transpositions outside the parallel were not in this case necessary. The manner of locating such power transpositions for capacitance balance is however shown in Fig. 3. When the grounded-neutral bank is disconnected from the system there is a considerable residual voltage due to the vertical configuration of the two lines *a b*. The line *a e* being triangular has a much lower capacitance unbalance. Moreoyer the ultimate replacement of the grounded-neutral bank by a delta-delta bank is contemplated. An attendant advantage of transposing this line throughout its length is the improvement of the power-system telephone circuit which is located on the power-circuit poles.

In view of these considerations it was deemed desirable to rely upon the efficacy of the coordinated transposition system and balance of telephone circuits to avoid interference from the triple-harmonic residuals due to the grounded-star transformer bank.

The plan devised for obtaining an approximate capacitance balance is outlined below. If the transpositions according to this scheme prove to be insufficient others can economically be added.

Considering first the two power circuits *a b* (see Fig. 3 Case II) operating in parallel, two 15-mile barrels are installed in each line.

The section involving the parallel *c,d,* is already balanced by virtue of the two barrels installed to co-ordinate with the telephone transposition system and provide longitudinal induction balance within the parallel. Hence one section, *a,c,*and a second section on the other side of the parallel, *d,e,* remain unbalanced. In the section *a,c,* there is an existing transposition, to be retained if possible. Therefore, two barrels of unequal length were installed in the section *a,c,* utilizing in one of them the existing transposition; by reversal of the two transpositions within the section of parallel *b,c,* Fig. 2, the proper type of exposure occurs in the section *d,e,* Fig. 3, which, considered with the section from the existing transposition to point *c* makes up the deficiency in length of the barrel. Hence capacitance balance is obtained by the use of two 19-mile barrels, although using a detached section of power line for balance. This case again illustrates the use of the reversed rotation of power-circuit transpositions.

It may be stated in connection with this case that the transpositions for capacitance balance and reduction of residual voltage in the power system have not, as yet, been installed. The reason that they were not installed, is that under the present conditions of operation the coordinated transposition system within the parallel was determined by test to be sufficient to provide the requisite relief and that the longitudinal effect of the present existing residual currents and voltages was sufficiently small not to warrant greater refinement at this time.

CASE III

In Case III (see illustration Case III) is given a typical example of parallelism between a telephone line and a power line operated isolated from ground. The details of this case are as follows:

Power System. 22,000 volts, three-phase, 60 cycles. All three conductors in same horizontal plane, spacings 35 and 65 inches. Delta-delta transformer connections at three stations. Three existing transpositions within the parallel.

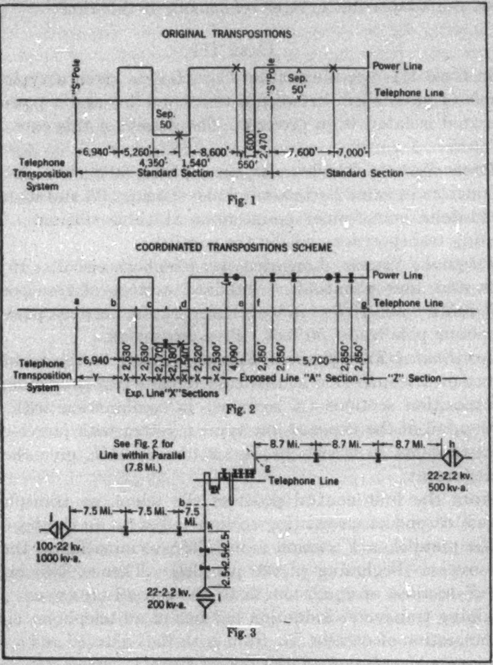
Telephone System. Long-distance telephone circuits; 10 physicals and four phantoms. Standard system of transposition.

Parallel. 38,970 feet in length; separation between power and telephone pole leads, 50 feet. Five crossovers.

Coordinated Transposition Scheme. Owing to the number of points of discontinuity in this case (crossovers) short telephone transposition sections (*X* sections) in combination with an *A* section, all of the exposed-line type, together with power-circuit transpositions as shown in Fig. 2 of Case III, give the best arrangement.

From the first neutral point of the telephone transposition system *a* (end of an existing section) adjacent to the beginning of the parallel, a *Y* section is installed, terminating at the first crossover *b* (beginning of the parallel). Thence, two exposed line *X* sections of equal length to the second crossover *c*, thus obtaining transverse induction balance of all telephone circuits in the section of parallel *b,c*, from both the balanced and residual currents and voltages of the power system. From the second crossover *c* to the third crossover *d*, three *X* sections are installed two of which are of equal length inserted between the crossover and the existing transposition in the power circuit. A transposition is installed in the power circuit opposite the junction point of the first two *X* sections. Transverse balance and approximate longitudinal balance to induction are accomplished by this arrangement in section *c,d*. If the existing transposition in the power circuit had been at one of the third-points of *c d*, exact longitudinal balance would have been obtained. It will be seen that here a sacrifice in longitudinal balance was made in order to retain an existing power transposition.

From the third crossover *d* to point *g*, the end of the parallel,


ORIGINAL TRANSPOSITIONS
"S" Pole
"S" Pole
Sep. 50'
Sep. 50
Power Line
Telephone Line
6,940'
5,260'
4,350'
1,540'
8,600'
1,600'
550'
2,470'
7,600'
7,000'
Telephone Transposition System
Standard Section
Standard Section
Fig. 1
COORDINATED TRANSPOSITIONS SCHEME
a
b
c
d
e
f
g
Power Line
Telephone Line
6,940
2,630'
2,630'
2,170'
2,180'
1,540'
2,520'
2,530'
4,090'
2,850'
2,850'
5,700
2,850'
2,850'
Telephone Transposition System
Y
X
Exposed Line "A" Section
"Z" Section
Exp. Line "X" Sections
Fig. 2
See Fig. 2 for Line within Parallel (7.8 Mi.)
8.7 Mi.
8.7 Mi.
8.7 Mi.
h
g
Telephone Line
22-2.2 kv. 500 kv-a.
b
7.5 Mi.
7.5 Mi.
7.5 Mi.
j
k
100-22 kv. 1000 kv-a.
2.5
2.5
2.5
2.5
22-2.2 kv. 200 kv-a.
i
Fig. 3

CASE III.

two *X* sections and one *A* section are installed. The exposed line *A* section is of such length that the pole at two-eighths of its length falls at the crossover point *f*. The two *X* sections are installed between the point *d* and the first pole in the *A* section and are of equal length. A power circuit transposition of reversed rotation is installed opposite the junction of the *A* and *X* sections, thus giving in combination with the section *b,c,* approximate longitudinal balance in the total section *b,c,* and *d,e.* The existing power transposition in section *d,e,* is removed. Whole-line transpositions are installed in the *A* section between the one-eighth and two-eighth points in order to reduce the transverse unbalance incurred due to the interruption in parallel from *e,f.* Thus, transverse balance has been obtained in the section of parallel *d,e.*

In section *f, g,* power transpositions are installed opposite the three-eighth, four-eighth, six-eighth and seven-eighth points of the *A* section, thus accomplishing longitudinal and transverse balance to induction in this section. The existing power transposition in the section *f, g,* is removed.

It will be seen that a coordinated system of power and telephone transpositions has been applied which balances to both transverse and longitudinal induction from the balanced voltages and currents of the power system, and transverse induction from the residuals of the power system.

Mitigation of Residuals. Since in this case an isolated system is involved and the flat configuration causes a large residual voltage, the remedial measure required is transposition of the power circuit outside the parallel in such a manner as to balance the capacitance to ground of the several phases.

In order to determine how small a number of transpositions would give relief in this case, it is proposed to install very long barrels in the sections of power line beyond the exposure, as indicated in Fig. 3. These will not be entirely effective if high-frequency components in the power circuit are prominent. The method of laying out these transpositions is as follows:

The transpositions of the power circuit within the parallel for longitudinal induction balance from the balanced voltages and currents also provide capacitance balance for this section of power line. It remains to transpose the section of line outside the parallel so that capacitance balance is obtained throughout.

In the section between one limit of the parallel *g* and the substation *h* (26 miles), one barrel is cut in the power line by installing two transpositions of normal rotation at the one-third and two-third points.

In the section between the other limit of the parallel *b* and substation *j* (22.5 miles), a barrel is cut in the power line by installing two transpositions of normal rotation at the one-hird and two third points.

The section from the power line junction point *k* to substation *i* (7.5 miles) is cared for in a like manner.

Thus, in each of the four sections cited, capacitance balance is obtained. Attention is called to the manner in which the practical considerations such as length of line and location of discontinuities arbitrarily determine the length (maximum) of power circuit barrel both from the standpoint of coordination of transpositions and measures for capacitance balance.

This case is one which was presented for solution in the field. However, for the purpose of simplifying the discussion, the extent of power system beyond either end of the parallel has been greatly reduced.

The above cases, it is thought, will serve to give a general idea of the practical methods pursued in the field for the solution of inductive interference problems. It must be remembered that the remedial measures set forth in the above cases are not necessarily applicable to other cases, and that each case requires a consideration of its particular conditions in order that adequate remedial measures may be provided.

In conclusion, we can say with conviction, based upon the facts cited in this paper and our actual experience, that the general problem of inductive interference involving three-phase circuits, while seemingly difficult of solution, is in fact, when fairly and reasonably approached, usually simple and inexpensive- The remedial measures employed, when properly designed and installed, are very effective. It is true that occasionally a problem will arise, the solution for which will impose some burden on one or both interests involved. When such a problem does arise, it is capable of solution only through a broad co-operative spirit between the two parties and their mutual willingness to bear such burden for the welfare of the community.

APPENDIX I

DATA REQUIRED IN CASES OF PARALLELISM

TO FACILITATE THE DETERMINATION OF REMEDIAL MEASURES FOR THE MITIGATION OF INDUCTIVE INTERFERENCE

The severity of the inductive interference with telephone service caused by any given parallel is dependent upon the physical characteristics of the parallel, the electrical characteristics and method of operation of the power system, and the condition of the telephone circuits. The following pages describe the data necessary for a study of a parallel to devise means for the prevention or reduction of inductive interference arising therefrom. In order that the best results may be secured, the instructions given herein concerning the preparation of the report transmitting the required data should be very carefully followed.

In the case of a proposed parallel, or general reconstruction of an existing parallel, a study shall be made to determine whether or not other routes are available, for either the telephone or power lines involved, which will avoid the parallel. A report on possible alternatives shall be presented in connection with the transmittal of other data concerning the parallel.

The forms and instruction of this circular have been devised to facilitate a complete report on parallels already in existence; the same general plan can be followed, however, for proposed parallels.

If any of the data are doubtful the best obtainable information shall be given and its degree of reliability stated.

A—Telephone and Power Line Data. A form for reporting the data regarding the power and telephone line is given. The form should be typed or mimeographed as convenience dictates. It is self-explanatory as to information required.

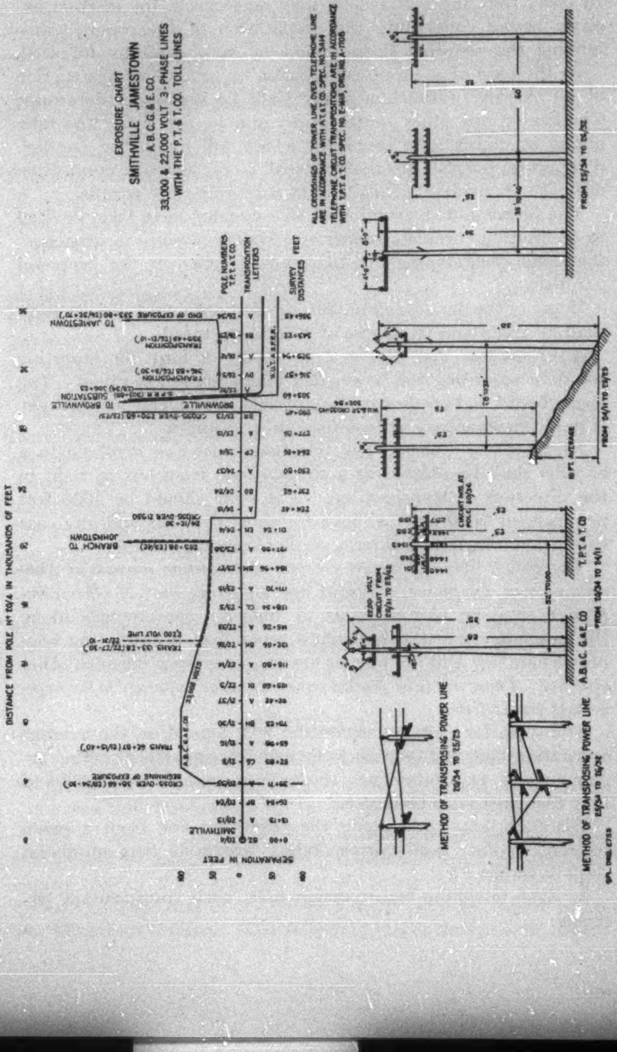
B—Exposure Chart. The telephone pole line involved in a parallel shall be plotted as a *straight line*, from left to right in the direction of transposition. The scale should be 4000 feet per inch, or 2000 feet per inch for short parallels and any case where complications render a smaller scale undesirable.

The power line *and all arc circuits, distribution circuits of* 2200 *volts or over, telephone, telegraph and signaling lines of other companies*, shall be plotted so as to indicate continuously along the telephone line the horizontal separation between the telephone pole line and the pole or tower lines supporting such other circuits. *These are to be plotted only within the exposure to the high-voltage power line.*

The scale for plotting separation will depend on the average separation; 50 feet per inch is usually convenient. The accompanying exposure chart, shows an example of a parallel and how the chart is to be plotted.

Distances measured along the telephone line from a given reference point, (and corresponding telephone pole numbers) shall be shown for:

a. Each telephone transposition pole, with transposition lettering.


EXPOSURE CHART
SMITHVILLE JAMESTOWN
A.B.C.G.&E.CO.
33,000 & 22,000 VOLT 3-PHASE LINES
WITH THE P.T.&T.CO. TOLL LINES
ALL CROSSINGS OF POWER LINE OVER TELEPHONE LINE ARE IN ACCORDANCE WITH A.T.&T.CO. SPEC. NO. 3414
TELEPHONE CIRCUIT TRANSPOSITIONS ARE IN ACCORDANCE WITH T.P.T.&T.CO. SPEC. NO. E-1418, DWG. NO. A-17106
POLE NUMBERS T.P.T.&T.CO.
TRANSPOSITION LETTERS
SURVEY DISTANCES FEET
SEPARATION IN FEET
DISTANCE FROM POLE No 20/4 IN THOUSANDS OF FEET
SMITHVILLE
TO JAMESTOWN
TO BROWNVILLE SUBSTATION
BRANCH TO JOHNSTOWN
2200 VOLT LINE
33,000 VOLTS
A.B.C.G.&E.CO.
CROSS-OVER
BEGINNING OF EXPOSURE
END OF EXPOSURE
TRANSPOSITION
A.B.&C. G.&E. CO
T.P.T.&T.CO
FROM 20/34 TO 24/11
FROM 24/11 TO 25/23
FROM 25/34 TO 26/32
METHOD OF TRANSPOSING POWER LINE 20/34 TO 25/23
METHOD OF TRANSPOSING POWER LINE 25/34 TO 26/32

b. Loading points.

c. Beginnings and ends of parallels.

d. Points where power lines cross over telephone lines.

e. Points where abrupt changes in separation occur.

f. Points where changes in configuration of power or telephone circuits occur.

g. Location of bridged stations and sections of cable in the telephone line.

h. Power-circuit transpositions.

i. Points where load or feeder branches connect with power line.

j. Places where there are spans of excessive length; river crossings, R. R. crossings, etc.

k. Each tower in case power circuit is supported on towers.

The chart shall contain as many sketches of the cross-section of the exposure as are needed to show the several types of construction, configuration and relative location of lines. A note under these shall specify the point at which each type begins and ends. These diagrams should show:

Vol. 35
1916

a. Average pole or tower heights.

b. Difference in elevation of ground under the two lines.

c. Dimensions to locate points of support and spacing of all wires on poles or towers.

d. Traffic numbers of telephone circuits with the number of the pole to which they apply.

A sketch shall be given showing the method employed in transposing the power line and number of poles involved in a transposition.

If special construction is employed at power line crossings, the details shall be given in the report.

Any special construction in the telephone line, such as at river crossing, shall be described in the report.

The chart shall contain a title including the number of the parallel, location, companies involved, voltage of power lines, and date.

The survey of the telephone line shall determine the location of telephone transposition poles, crossovers, power-circuit transposition poles, and other features to at least the nearest 10 feet. This distance should be the "wire distance", where obtainable from the records.

Horizontal separation of pole lines shall be measured within 2½ per cent (thus, where the separation is 20 feet, it shall be obtained to the nearest foot, if 100 feet, to the nearest five feet). The heights of wires above the ground shall be given to the nearest foot. The horizontal and vertical distances between wires of a power circuit and wire spacing on the telephone line shall be given to the nearest inch.

Many minor irregularities must be neglected, but the purpose should be to present the average conditions as faithfully as practicable, and to give data of all pronounced changes in the character of construction.

C—Circuit Diagram of Power System. Much of the required information concerning the power circuit can be shown diagrammatically as indicated in accompanying illustration. This diagram shall show:

a. All lines or apparatus *metallically* connected to the power circuits involved. Auto-transformers constitute metallic connections between lines of different voltages, hence the circuit diagram should not terminate in such transformers. Lines or apparatus which are connected to the circuit involved in the parallel by two-coil transformers are not required to be shown.

b. Method of connection of both primary and secondary sides of all transformer banks connected to the circuits. Indicate particularly the condition of all neutrals, whether grounded or not. Where single-phase, open delta or Scott connections occur, the particular phase, to which each wire is connected shall be shown.

c. Type and location of air and oil switches.

d. Type, location and connections of lightning arresters.

e. Location and ratio of potential and current transformers; location and range of ammeters in neutral ground connections.

f. Transpositions in the power circuits.

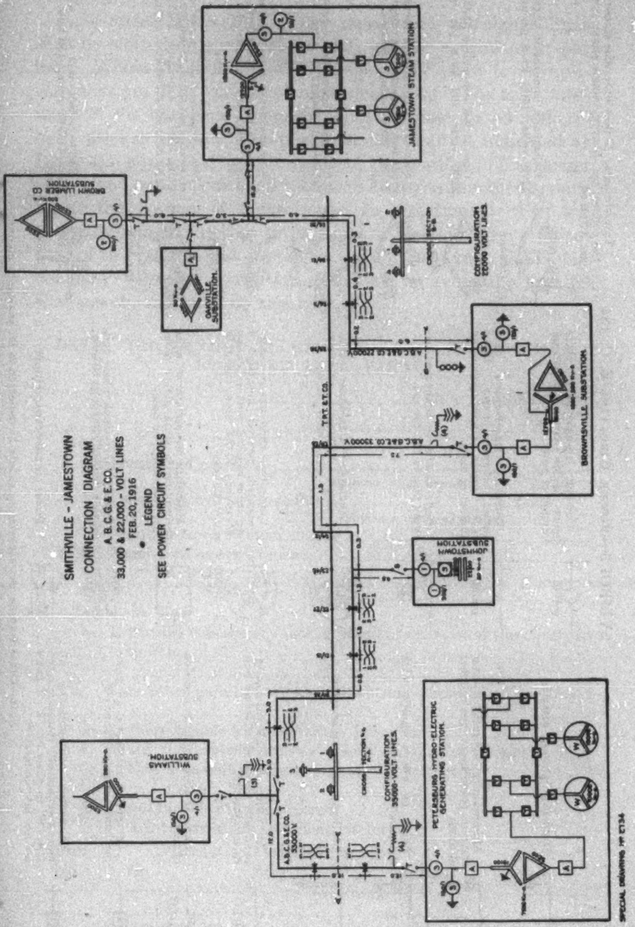
g. The length of power circuit between all points of importance, such as stations, branch points, transposition points, and points where configuration changes, to the nearest 0.1 mile.

h. Voltages and capacities of transformers or other apparatus connected to the circuit.

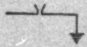
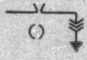
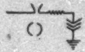
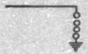
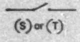
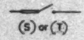
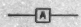
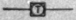
i. A cross-section of the power circuit at some one point with the conductors numbered to show their respective positions. If there are two or more circuits, the wires composing each shall be designated.

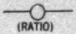
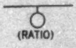
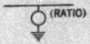
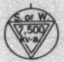
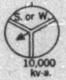
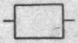
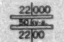
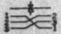
The title should include name of power company, number of the parallel, location, voltage of power circuits, date and legend.

A list of symbols for use in making up power-circuit connection

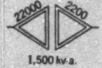
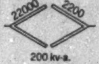
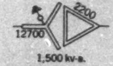
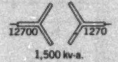
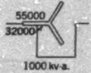
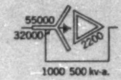
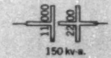

SMITHVILLE - JAMESTOWN
CONNECTION DIAGRAM
A. B. C. G. & E. CO.
33,000 & 22,000 - VOLT LINES
FEB. 20, 1916
● LEGEND
SEE POWER CIRCUIT SYMBOLS
JAMESTOWN STEAM STATION.
BROWN LUMBER CO. SUBSTATION.
OAKVILLE SUBSTATION.
BROWNSVILLE SUBSTATION.
JOHNSTOWN SUBSTATION
WILLIAMS SUBSTATION.
PETERSBURG HYDRO-ELECTRIC GENERATING STATION.
CONFIGURATION 22000 VOLT LINES.
CONFIGURATION 33000-VOLT LINES.
T.P.T.&T.CO.
A.B.C.G.&E.CO. 22000V
A.B.C.G.&E.CO. 33000V
A.B.C.G.&E.CO. 33000 V
SPECIAL DRAWING

SYMBOLS—POWER CIRCUITS—E. C. 134

	Horn-gap lightning arrester.
	Aluminum-cell lightning arrester state in parentheses the number of units.
	Same as above except with charging resistances.
	Multigap lightning arrester.
	Air Switch S-single poles independently operated. T-three pole interconnected.
	Same as above with the addition of fuses.
	Oil switch automatic all poles mechanically interconnected.
	Oil switch non-automatic all poles mechanically interconnected Use "S" in place of "T" if poles are not interconnected.

	Current transformers place figure inside circle indicating number of units.
	Potential transformers connected between phases. Place figure inside circle indicating number of units.
	Same as above—connected between phases and ground.
 S. or W. 7,500 kv-a.	Generator—three-phase delta-connected 7500-kv-a. S-steam driven W-water wheel driven
 S. or W. 10,000 kv-a.	Generator—three-phase star-connected, neutral grounded, (if neutral is isolated omit indication of ground) 10,000 kv-a. (S and W same as above.)
	Miscellaneous apparatus write description in rectangle or reference to descriptive note.
 22000 50 kv-a. 2200	Transformer—single-phase connection 22,000/2200 volts 50 kv-a.
	Power circuit transposition.

Transformers. Unless otherwise stated on the connection diagram single-phase units are assumed.

 22000 2200 1,500 kv-a.	Delta-delta connection 22,000/2200 volts, 1500 kv-a. per unit.
 22000 2200 200 kv-a.	Open-delta connection 22,000/2200 volts, 200 kv-a. per unit.
 12700 2200 1,500 kv-a.	Star-delta connection neutral grounded, ammeter in neutral 12,700/2200 volts, 150 kv-a. per unit.
 12700 1270 1,500 kv-a.	Star-star connection neutral isolated 12,700/1270 volts, 1500 kv-a. per unit.
 55000 32000 1000 kv-a.	Star-connected auto-transformers neutral isolated. 55,000/32,000 volts. 1000 k-va. per unit.
 55000 32000 2200 1000 500 kv-a.	Star-connected auto transformers neutral grounded, 55,000/32,000 volts, 1000 kv-a. per unit. Tertiary delta 2200 volts, 500 kv-a. per unit.
 11000 2200 150 kv-a.	Scott-connection 2 to 3 phase 2200/11,000 volts, 150 kv-a. per unit.

Note—Other transformer connections should be indicated in an analogous manner.

diagrams, in the manner shown in the illustration, is given herewith.

D. General Route-Map. The power and telephone lines shall be plotted on a map whose scale may be several miles per inch. Where available, the U. S. Geological Survey topographical maps are very convenient for this purpose. The toll route-maps of the telephone company can sometimes be advantageously used as a basis. The telephone line shall be indicated as far as the adjacent *S* poles outside of the parallel. The power circuit and substations shall be shown to an extent corresponding to the diagram of connections. In case the extent of the power system makes this impractical, a separate geographical map of the system shall, if possible, be obtained from the power company. Possible routes for either line to avoid the parallel shall also be indicated on this map.

DATA CONCERNING TELEPHONE AND POWER LINES INVOLVED IN A PARALLEL

..................................Division Parallel No.......

....191.......

I. General

1. Location of parallel..
(Between what towns?) (State)
2. Length, along telephone line..................................miles.
(distance between limits)
3. Name of power company..
4. Number of power circuits..
5. Is the parallel existent or proposed?..
6. Which is the senior company?..

II. Telephone Line

1. If parallel is existent, state in detail the nature of the observed trouble..
....
2. What other parallels are there involving these telephone lines?
....
3. Is there trouble from secondary induction?...................................
4. State the present physical condition of the telephone line. How soon will it require general reconstruction? ....
....
5. Insulation of telephone circuits
Relative noise on telephone circuits

Circuit No.	Insulation-Megohms per mile			Relative* Noise %
	Tip	Ring	Mutual	
....	....	....	....	....

*Estimate noise in per cent of noise on noisest circuit rated at 100 per cent.

6. What is the ultimate capacity of the telephone line?
....

7. State specification and drawing numbers of telephone transposition system..
....

8. If any circuits are loaded, state the location of loading points, give pole numbers within the parallel and at the adjacent loading points outside of the exposure, and state whether or not loading point is an **H** fixture..
....

9. What types of insulators are used on the telephone line?............
....

What types of insulators are used at loading points?..............
....

10. If the apparatus connected to any circuit is not standard T. P. T. & T. Co. equipment, describe it................................
....

11. State location of any points within the parallel at which circuits enter cable (*e.g.*, river-crossings). Give specification number of cable..
....

12. Do any circuits branch from the telephone line within the exposure? If so, state traffic numbers and points of branching. If local circuits are also involved in the parallel, give their points of branching...
....

13. Telephone Circuits involved in the Parallel

Traffic No.	Physical or phantom	Size & material of wire	Loaded or non-loaded	Terminals
....	....	....	....	....

14. Describe special construction in telephone line at river crossings, etc...
....

15. State any other pertinent information......................................
....

III. Power Circuit No.............................*)

1. Voltage..
(actual operating voltage between wires)
2. Number of phases......................, Frequency.................cycles per sec.
3. Power circuit supplied from......................................Station.....
4. Power circuit supplies energy to...
....
5. Character of load, motor, lighting or both....................................
....
6. Average current per phase..amperes.
7. Average daily maximum current....................................amperes.

---

*If there are two or more power circuits they should be reported separately and every sheet marked to indicate (by number) the particular circuit reported thereon.

8. Hour at which peak load occurs..

9. If the neutral points are grounded, are there ammeters in the neutral connections?..

10. State their range..

11. Are they connected directly or through current transformers?
....

12. Give ratio of transformation..
....
What is the average neutral current?........................amperes.

13. Size of conductors..ga.
Material of conductors..

14. In case the power line is existent, state its present physical condition. How soon will it require general reconstruction?
....

15. Type of insulators..
Are the insulator pins grounded?..
If suspension insulators, state number of discs........................

16. Lightning arresters.

Location	Type	Connections	Frequency and time of day of charging	Charging current-amperes per phase
....	....	....	....	....

What is the method of charging?..
....

17. Switches

Location	Type	Mechanically interconnected for simultaneous action?	What devices are there for automatic operation of switches?
....	....	....	....

18. Transformers

Location	No. of units	Mfr.	Kv-a. rating	Voltage rating	Form No. etc.	Single or three-phase	If three-phase, shell or core type
....	....	....	....	....	....	....	....

19. Rotating apparatus. If generators, motors or converters, etc., are metallically connected to a circuit involved in a parallel or if such circuit connects directly to a generating station, give data as to

Kind of Apparatus	Location	No. of units	Mfr.	Type	Kv-a. rating	Voltage rating	Electrical connection
....	....	....	....	....	....	....	....

20. State other pertinent information..
....

DISCUSSION ON "INDUCTIVE INTERFERENCE AS A PRACTICAL PROBLEM" (GRISWOLD AND MASTICK), SEATTLE, WASH., SEPTEMBER 6, 1916.

Frederick Bedell: Remedial measures for inductive disturbances are necessary because we do not have perfect telephone circuits, nor perfect power circuits, nor perfect power generators. By improving the wave-form of the power generators—that is, by making the wave-form more nearly a pure sine wave—inductive disturbance and the necessity of remedial measures can be reduced, as is pointed out in the paper; but in all probability the best that can be done in the design of machinery, without prohibitive expense, will only reduce, but not eliminate the disturbance. The problem of remedial measures will still remain, but it will be an easier problem. A standard of wave-form, in this connection, is seen to be desirable.

L. T. Merwin: The authors' paper presents one consistent scheme only for overcoming the troubles of inductive interference Unquestionably, the telephone companies have made elaborate experiments as to the possibility of developing other means of overcoming the troubles. So far as I know, the power companies have done little or nothing along this line. It would be extremely interesting to us, as power men, to know what other remedial measures were tried, and, if tried, why they were abandoned. I would like to ask Mr. Mastick if the telephone companies have tried, for instance a scheme that appears to me to have some value, and, if they have, what were the results: For example, is it possible to so modify the Thompson system of telephone line loading with inductive shunts, that those shunts instead of giving a straight line function, for the *j* component of the impedance which would be obtained with inductive character only—would give an approximate straight line function for all frequencies above, for instance, the 5th or the 7th harmonic of a 60-cycle system, and a sharply divergent or logarithmic function for all frequencies below? In other words, that the shunts would perform two functions, namely, that of providing a short-circuit path for low frequencies; and, on the other hand, perform the same service as the inductive shunts of the Thompson system of loading for the higher frequencies, namely, that of producing a distortionless line—laying aside the matter of attenuation for the present—for frequencies within the usual range of voice currents, but producing short-circuit paths for these troublesome 3d, 7th and 9th harmonics of the 60-cycle system. Have the telephone companies experimented with series impedances in their lines of such a nature that the series impedances if judiciously placed, would produce a high resultant impedance for all low frequencies, and yet produce a straight line function of the Pupin type of loading for all frequencies say from the 9th harmonic of the 60-cycle system up through the range of the voice frequencies? If methods of this sort, or of any similar sort have been tried, it would be extremely interesting to us to know what were the difficulties encountered, and why they were abandoned. Any scheme of transposition, that is laid out, involves the expenditure of money, and it is only natural that when the power companies, themselves, are only concerned, in so far as the reaction of the trouble may lead to force expenditure, it is only right, I say, that we should ask of those who are fitted to answer—the telephone engineers themselves—as to the possibilities of other methods of overcoming the troubles.

J. B. Fisken: Two years ago the power engineers were pretty much alarmed at what they learned regarding the California order, and it looked as if we might possibly have to go into the hands of receivers or go out of business. It does not look as bad to me now as it did then. It looks as if a good many cases could be taken care of without prohibitory expense. One question I want to ask Mr. Mastick is whether I am right in supposing that the flat construction of a line is more detrimental, in that it produces more residual voltages than the triangular construction? I have had some experience with a line of flat construction 65 miles in length, and this line was built to avoid, as far as possible, paralleling the telephone toll lines, although, to some extent, it does parallel them, and we had nothing brought to our attention to lead us to believe that the flat construction was objectionable. Of course, it is transposed, just the same as a triangular construction, and we have had nothing to indicate that the residuals are serious on that line. It begins to look as if we had to take care of two features of construction, or, rather, one feature of construction and one feature of design of apparatus; the feature of construction being the location of transpositions, which, to my mind, unless our telephone friends insist on putting them in too frequently, are not objectionable; and the other of getting rid of the higher frequencies, which, I think, are just about as objectionable to the power men as they are to telephone engineers.

W. D. Peaslee: There is another feature that has not been mentioned in the paper, that is of considerable importance, I think, in the interference of a power line with a telephone line, and that is the effect of the continual corona discharge on a defective insulator, and also the effect, which I have seen on a great many of the lines, in the northwest, especially when they have taken to grounding the insulator pins on wooden poles. On a great many of those lines, you will see the ground wire connection to the insulator pin, loose, and at night, you will see a continuous discharge from the line into the condenser of the insulator from this loose connection. In a short study of that, I took an insulator—a standard, 60,000-volt, pin-type insulator—and putting on an artificial line with loose connection to a pin of that nature, with an ordinary coil of wire containing 300 feet and a telephone receiver, I have succeeded in getting considerable disturbance into the coil of wire. I would like to know if Mr. Mastick has encountered any situation of that kind, wherein the transmission of such disturbance on the transmission line into the telephone circuit occurs. Being of high frequency, and oscillatory in character, it would be a very difficult thing to get rid of, and also, a defective insulator, always produces a high-frequency discharge or oscillation in the power line. These discharges are very troublesome to the power people, and I would like to know in that connection, also, if interference has been encountered with this static inductance, with these ground connections showing up in the telephone line, either as a bat in the telephone receiver, or as a continuous high-frequency disturbance.

R. F. Robinson: In answer to that last question, I had something to do a few years ago with a line, where there was a great deal of trouble with the charging of the electrolytic lightning arresters. We made some tests with the power man, and had him vary the way in which he charged the arrester. He drew, for instance a very short, quick arc, that made very much less disturbance in the telephone line that when he drew out a long arc and held it for a long time. In drawing that long arc, it seemed to put the telephone line out of business all the time that the arc was held. The results on that line on account of the trouble were rather serious. There had been two or three cases of persons being injured while using the telephone line at the time the charging operation was taking place. In one case, a lady who was using the public telephone in a booth, was rendered unconscious during the time of this electrolytic charging. The answer seems to be indicated in this paper, that it is a matter for co-operation of the telephone companies and the power companies. The telephone people have probably done more studying on these questions, and in many cases, they have come to the conclusion, "Well, it is up to the power people. We can't do anything more." The power people on the other hand, say "It is not our trouble. Let us leave it to the telephone people. They have got to figure out some way to get around it." But this paper very clearly indicates, I think, that it is impossible for either the telephone companies or the power companies to do all the work to overcome this induction trouble, but they must work together, and design the necessary means to get around the trouble at the least expense to both companies. Apparently, that consideration was one of importance in designing these transpositions which have been brought out here—that neither the telephone nor the power company should be put to any unnecessary expense or any unnecessary work on their lines, which could be avoided by co-operation on the part of the other company.

L. J. Corbett: Two years ago the investigations on inductive interference had just been started and a working rule was inaugurated and adopted in California. Only the simplest circuits, if I remember rightly, were taken up. At the present time, we have a great many different types of lines and interference cases analyzed. In time I presume all possible cases will be worked out, or we will be able to analyze all cases as combinations of certain cases which can be classified properly. I wish to call up the matter of the transmission line which crosses the telephone line at an angle of 20 degrees. I would like to ask Mr. Mastick if any investigations have been made upon such cases, because it seems to me that the effect would be greatest at the point where the line crosses, and as the departure becomes greater and greater, the influence, of course, would become less and less. In that case the interference would not be a true cosine function. I would like to ask also if they have investigated cases containing phantom circuits as applied to these schemes. That undoubtedly will have to be taken up, and I presume that in some of these complicated cases the addition of phantom circuits will complicate the matter even more, where a great many lines cross the power line.

C. A. Whipple: I have had occasion to investigate a number of cases of telephone troubles in connection with their proximity to power lines, and in all cases, I have found that the difficulties arising from the application of these rules, as set forth in the paper, have arisen from one of two conditions: Either the construction of the transpositions was not done in accordance with the instructions of the engineers, or there were defective insulators or other apparatus which caused these difficulties. In many cases the engineers relied upon those in the field to accurately place the transpositions where indicated. Investigation showed that in almost all cases the field work inaccurately done, sometimes the transposition points being but a few feet off, but the accumulation of a few feet on various sections of transposition lengths was cumulative, thus making quite a distinct disturbance upon the telephone line as a whole. In other cases, the discharge from defective insulators or the static effect of other apparatus in the near vicinity produced the effect upon the telephone system. These defects threw considerable disrepute upon the method. But it was not the method that was at fault, it was the execution of the method in the field.

J. B. Fisken: Mr. Mastick in his paper recommends that the neutral grounds be applied only at the power stations and important switching stations. Apart, altogether, from the question of inductive interference, I thoroughly approve of that recommendation. I have had some experience both ways. When we first installed our 60,000-volt distribution line, we grounded the neutrals of all our transformers, but after a few years experience with that method, we removed those grounds except at the power stations just as fast as we could. There was one experience we had, where a line switch was dead-ended, on insulators with very short connections, with solid wire to the switch itself. One of those connections broke, and before we found it the railroad in that vicinity was operating trains with flag signals; they had no apparatus left; and the telephones, of course were entirely out of business. It took us some time to find the break, because it was only about half an inch, and could hardly be seen from the ground. We found it by repeated experiments in trying the line and finally one man saw a flash, examined it, and found the wire broken. In many cases, the transformer itself does not give an absolutely true neutral, and if the transformers have neutrals grounded all over, there will be a slight interchange of current between them, which is not serious from the power man's standpoint, but I conceive might be quite serious from the telephone man's standpoint.

L. T. Merwin: If the telephone companies have experimented along other lines of remedial measures, as suggested in my previous remarks, I would like to ask, if a distortionless line was obtained at the expense of great attenuation, what percentage attenuation would be considered the limit that could be utilized and yet be not objectionable, by reason of modern methods of amplification in use by the telephone companies, either mechanical or of the audion bulb type.

R. W. Mastick: It seems desirable before replying to specific questions to discuss briefly the subject of "Noise" in telephone circuits which are exposed to high-tension power circuits, since in the main the discussions have borne directly on the elimination of noise by means other than those described in the paper.

The noise induced in a telephone circuit by the paralleling power circuit is usually due to several currents of various frequencies, viz., the fundamental, third, fifth, seventh, ninth, etc., harmonics. The fundamental is, however, from the standpoint of noise production, practically unimportant as compared with currents of higher frequencies. Analyses of noise currents have indicated the presence of frequencies from 50 cycles up to 2000 cycles and more.

The telephone speech current is of a very complex character, being a combination of a large number of waves of different frequencies, of which the most important waves lie within the range of the noise-current frequencies, that is, between 200 and 2000 cycles.

The detrimental effect of noise currents on telephone conversations increases very rapidly with the frequency up to a point near 800 cycles (which represents roughly the average frequency of voice currents and at which point therefore telephone apparatus is of maximum sensitiveness). For higher frequencies, the effect is gradually reduced. Since the frequencies present in noise are also those present in speech within the most important range of the latter, it can be seen that the application of a device in the telephone circuit whose successful action is based on the short-circuiting of the noise currents to the exclusion of speech currents is not generally feasible.

Mr. Merwin has suggested the possibility of modifying the Thompson shunt method of loading so as to short-circuit the noise currents below a certain frequency, and yet obtain the advantages of loading for all higher frequencies. The studies of this method of loading by telephone engineers have shown it to be generally unsatisfactory, because it is not possible to obtain sensibly uniform attenuation of all frequencies within the range of speech. In other words, the Thompson method of loading is inherently inefficient except for a small range of frequencies near the particular frequency of maximum efficiency for which the loading is designed. This method has also the disadvantage that it is not adapted to the use of superimposed telegraph on the telephone circuit, which practise is used to a large extent by the telephone companies.

The application of series impedances that Mr. Merwin has mentioned, is, of course, the principle of the present method of telephone circuit loading. Such arrangement gives a sensibly uniform attenuation of all frequencies up to a frequency determined by the coil design and spacing. Above this frequency which is always the upper limit of voice frequencies, the attenuation rapidly increases. Hence it is not possible to use this system of loading to exclude the lower frequencies in the range of noise currents.

Commenting further on both of Mr. Merwin's suggestions, it should be pointed out that it is not sufficient to exclude the noise frequencies below the ninth harmonic, but also those above must be eliminated since the detrimental effect of higher frequencies particularly in the vicinity of 800 cycles is far greater than the low frequencies. The 11th, 13th, 15th and 17th harmonics occur in present-day power-circuit waves in sufficient amount to require serious consideration in any attempt to mitigate inductive interference.

Configuration of the power circuit and its bearing on magnitude of induction and the residual voltage of an isolated system as mentioned by Mr. Fisken are of great importance. Studies have shown that the residual voltage of triangular lines is less than that of horizontal or vertical lines and that the horizontal configuration with unequal spacing of conductors is productive of the largest residual voltage found in practical cases. With respect to magnitude of induction from various configurations, the triangular configuration is generally to be preferred. However, the severity of the induction is governed by the relative location of the two lines with respect to separation, height of wires above ground, depth of ground plane for magnetic and electric phenomena, etc. For specific cases computations can be made which will indicate the best type of configuration to use.

The matter of discharges over defective insulators, mentioned by Mr. Peaselee, is a source of much concern to telephone companies. They are manifest in the telephone circuit as disagreeable cracklings, if intermittent, and in the event of total failure of the insulator, as very severe noises sufficient sometimes to temporarily deafen the telephone user. Total failure of an insulator generally creates a bad unbalance of the power circuit producing large residual voltages or currents which, of course, induce harmful voltages on paralleling telephone circuits. These induced voltages are frequently of sufficient magnitude to operate the telephone line protectors.

From the standpoint of inductive interference, angular crossings, as mentioned by Mr. Corbett if of fairly large angles, are usually not serious enough to require remedial measures. Some work of a mathematical nature has been carried out for a case in which a power line of high voltage crossed a telephone line at an angle of 30 degrees, and the results therefrom bear out the above assertion. However, if the angle of crossing is so small that quite an appreciable distance is required from the crossover to obtain a large separation between the two lines, some measures would generally be required.

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the American Institute of Electrical Engineers,
Seattle, Wash., September 6, 1916.

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TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES

BY B. G. FLAHERTY

Abstract of Paper

This paper discusses the importance and necessity of field tests on high-tension insulators and three methods of making such tests, viz., with the oscillator, the megger, and the telephone receiver. The latter is described in detail, and some data given on its development and use on a 60,000-volt line in western Washington, covering a period of 2.5 years. Laboratory checks on 13 of the defective insulators located, are given, and an approximate relation established between the telephone receiver test and the break-down value at 60 cycles. Success of test is shown in note on its effect on operation.

Figures from regular routine tests show percentage defect on various lines, and cost of locating and replacing defective units is given at $1.13 each (labor only), and cost of testing only was 2.3 cents per insulator on the line.

A method of studying the rate of depreciation is outlined and some data given in illustration.

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Introduction

MOST of the literature dealing with the failure of insulators on high-tension lines, treats almost entirely with the question from the point of view of improving the quality of the future insulator by various means of manufacturing improvements and specifications for testing before putting into use on the line. It does not deal to any considerable extent with methods of locating defective insulators among the great number already in service. While it may be admitted, without question, that the evolution of better insulation for future use is the most important need, the treatment and handling of the large quantity of insulators already installed should not be neglected. In fact this problem becomes the most serious one to the operating man, both from the standpoint of preserving the continuity of service, and of conserving as much as possible the large investment in the stock of the insulators in use.

Formerly, there was considerable discussion and argument about the depreciation of the porcelain in line insulators, though the majority of recent opinion seems to deny the depreciation *per se* and attributes failures after a period of service to various causes; such as inherent faults in the part as it comes from the firing, troubles due to improper cementing together of parts, or the use of cemented-in iron pins, causing unequal expansion. There is, however, no denial of the fact of deterioration of the insulator considered as a unit, *i.e.*, failure after a period of service. Undoubtedly a great deal can be, and has already been done to improve the quality of the porcelain; and by laboratory tests, to weed out the defective units in the process of manufacture and distribution. To this end the Transmission Committee has evolved the " Specifications for Insulator Testing ", dealing almost entirely with factory tests.

More important to the man now operating high-tension lines is some means of locating the defective insulators he already has on the line, thus affording him an opportunity to improve his factor of safety, and to preserve continuity of service, to which insulator failures have been in the past such a menace. Such a device, or devices, should be cheap, both as to first cost and as to methods of use; and should be reliable within practical limits. Too much expense either in first cost, or labor involved, could not be put into this class of work without approaching the point where it would be more economical to put in new insulation throughout. As yet, only three methods of testing insulators already in use on the line have been suggested; the oscillation transformer, the megger system, and the use directly of the telephone receiver.

The use of the oscillation transformer is recommended by Prof. E. E. F. Creighton and clearly outlined as to connections and adaptation in the TRANSACTIONS of the A. I. E. E. (Vol. XXXIII, 1914, p. 1122). The data given in the discussion indicate that it is very satisfactory as a high-frequency test and capable of being made very severe. Its availability and simplicity as a laboratory method for new insulators or those that have been removed from the line is evident; but its adaptability to service in the field is not so evident, presenting many difficulties. In the first place, in testing insulators on a line in actual service, it would be necessary to take the line out of service during the period of test; or to remove a quantity of insulators from the line, crate, transport, uncrate, test and replace on system, making the test prohibitive in cost. Also in attempting field work, a considerable crew would be required to handle and operate the apparatus and to make connections to each individual insulator, removing the line wire for the test. Another difficulty would be the source of current for the testing apparatus at all points of the line. These difficulties make the method impracticable for field work.

The megger test has become so commonly used throughout the country, especially on suspension insulator work, that it needs no description here. Mr. T. A. Worcester (*General Electric Review*, June, 1914, page 600) gives a thorough statement of the uses and limitations of this means of locating defective insulators. His main deduction is that it is not unconditionally reliable, being primarily a measure of the resistance, which may be practically "infinity" on a broken or punctured insulator unless contact is made directly with the defect and the latter is made conducting by the application of moisture. Another objection to the use of the megger for this purpose, is the necessity of "killing" the line under test for considerable periods and the use of a crew of men to make connections and remove the line wires from the insulators. It seems more particularly adaptable to testing the separate units of suspension-type insulators.

The use of the telephone receiver in the detection of defective insulators is mentioned by Mr. M. T. Crawford (TRANS. A.I.E.E., Vol. XXXIII, 1914, p. 1433), and it is with the development and use of this method that the present paper has to deal. Mr. P. H. Thomas (page 143, same volume) says, "We must find some way of detecting bad insulators. That can partly be done by tests, but we need a few new tests." If it can be shown that the test is reliable to a reasonable degree, it is evidently the most ideal method yet suggested, in that the actual testing can all be done by one lineman of reasonably good judgment and hearing, and also without any interference with the operation of the line, *i.e.*, the test is made at line voltage and frequency.

APPARATUS AND USE

The apparatus as developed for use on wooden poles is shown in Fig. 1. The double head set receiver is used to the best advantage as it aids in excluding foreign sounds, and focuses the observer's attention more closely on the work in hand. Almost any telephone receiver is found to be serviceable so that patrolmen in their routine work may use the receiver in the portable test set which they carry with them to locate the worst cases of defect. Where greater sensitiveness is required, the two thousand ohm wireless set shown in the illustration is found to give the best results, with the two units connected in parallel. The flexible cord used for connections is fastened by a small nut to the lineman's spur at one end, this serving as the ground terminal; and by a double connector to the large stiff wire run through the bamboo stick and sharpened to a point for contacting to the pole; *i.e.*, shunting a portion of the current flowing in the pole, through the receivers to ground. This, with the lineman's spurs and belt and proper notebook constitutes all the equipment necessary for locating defective insulators on pole lines using pin-type insulators. For use on steel tower lines using pin-type or suspension insulators the modifications are slight, looking more toward the safety and protection of the observer than anything else. The upper terminal is extended to a miniature wireless antennae, either in the form of radial spokes of a wheel, or a circular plate, and is used to explore the electrostatic field in the neighborhood of the insulator instead of measuring the actual current flowing over and through the insulator. Slightly greater sensitiveness is necessary for these cases and a higher resistance receiver with the units connected in series is recommended. The principal difficulty with this method is in protecting the operator from accidental contact with the high-tension wires. This is accomplished by covering the terminal with an inverted basket of wooden strips of dimensions sufficient to give proper clearance of four times the needle-gap spark value for line voltage to ground.

Two qualifications are necessary to the successful observer at this work; first, that he should be a good lineman, capable of going up and down, and working on the pole or tower near high-tension lines with quickness, steadiness, and assurance; and second, he should have good hearing. It is not especially important that he should be a technically trained man, although a little laboratory training and knowledge of electrical phenomena will help him considerably in the interpretations of the various sounds he will find throughout his experience of this work. The ordinary first class lineman of average intelligence can be taught by example to use the set and give a first rate judgment of defects indicated, in a few minutes time. Scientific truthfulness, *i.e.*, the faculty of setting down results as they actually come to him rather than as he believes he should get them, is also an important requisite. Absolute accuracy in

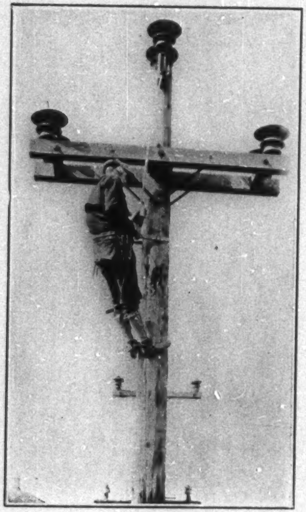

FIG. 1 [FLAHERTY]

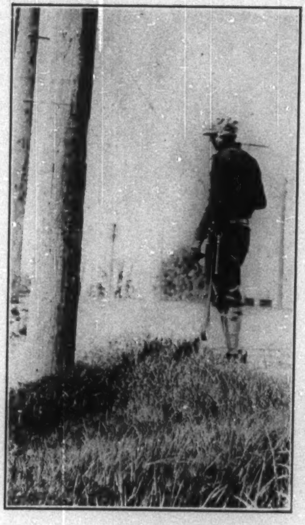

FIG. 1a [FLAHERTY]

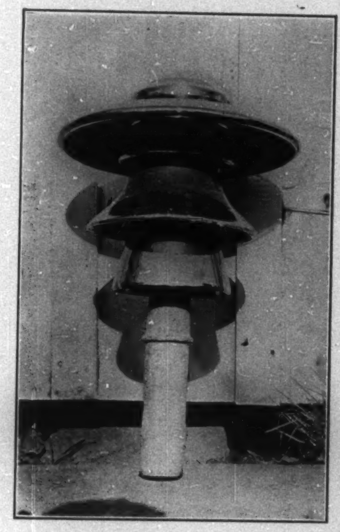

FIG. 4 [FLAHERTY]

keeping the records of the test is imperative if it is to be of any value in eliminating the defective insulators afterwards. Ordinary surveyor's field books are found to be most serviceable in use over the varied country which most transmission lines follow. The inspector in traveling along the line sets down the pole number and the result of the test on the ground. Four degrees of defect or leakage are arbitrarily assumed, namely, zero, first, second and third. The judgment of the observer must be depended upon to place properly the sounds heard. If the pole test indicates zero leakage it is not necessary to deal further with that one. If any leakage is heard, the inspector proceeds up the pole and tests to each insulator pin, or slides the point out along the crossarm or up the pole top if apprehensive of danger from too bad an insulator. Beginning at the left hand crossarm position, and looking in the direction in which the line is numbered, the insulators are numbered clockwise over the pole top in the case of equilateral construction. In vertical construction they are numbered from bottom to top. If more than one insulator supports the wire in each position on the pole or tower, the respective units are given sub-letter designations, as 1-a, 1-b, for double construction. Fig. 2 shows

INSULATOR TEST TACOMA No. 1 LINE

Pole No.	Pole test	No. 1	No. 2	No. 3	Remarks
2585	0				Fife, Station, P. S. E. Ry.
87	3	3	3	1	Date: 4-10-16
89	0				Observer: McGandy
91	1	0	1	0	Weather: Fair, clear
93	0				Ground: Moist, tide
95	0				flat level.
97	2	1	1	2	
99	3	3	0	0	
2601	3	0	3	0	
03	0				
05	0				
07	0				
09	0				
11	3	0	1	3	
13	0				
15	3	3	2	1	
17	0				
19	0				
21	0				
23	0	0	0	0	Climbed as check on former test
25	0				
27	0				
29	0				
31	0				
33	0				Gardenville Station.

FIG. 2

a sample page from the standard note book used. Only one man is necessary for this work, but the practise so far has been to send along a helper who is ready to climb to the other's assistance in an emergency, and this man can expedite the work considerably by keeping the record.

Weather conditions have considerable influence on the testing work through their effect, both on the insulator itself, and the working conditions of the test apparatus. Rainy or foggy weather increases the leakage over the insulators, especially if there is a deposit of dust, smoke, or other foreign matter, to such an extent that the exercise of a good deal of judgment on these effects is necessary in testing to keep from condemning a great many good insulator units. If rain is falling it is impossible to use the testing set, as the drops about the head and receivers shut out all other sounds effectually; and work on "bad" insulators on the pole top becomes literally "hair-raising". The ideal time to make this sort of test is when the sky is clear and the ground slightly moist underfoot to afford a good ground connection.

THEORY OF ACTION

The discussion of the theory of action here advanced is based on the pin-type insulator on wooden poles, but may be adapted to the other cases. The pin-type line insulator may be considered as a resistance shunted by a number of small condensers connected between the line wire and ground, and some idea of the magnitude of the currents flowing in such circuit may be obtained from measurements already published. Just to show that the resistance component of the current over the insulator from line to ground is of an appreciable value for measurement in the telephone receiver, Mr. Ralph D. Mershon may be cited (Vol. XXVII, TRANS. A. I. E. E.) as giving the power loss per insulator as between 40 and 75 watts at 50 kilovolts. From this it is readily seen that the effective value is sufficiently large to give considerable indication at 60 cycles, a-c., in an ordinary receiver, which is sensitive to a millionth of an ampere. Some idea of the relative magnitude of the capacity component may be obtained from Mr. Edward Bennett's statement (A. I. E. E. TRANS. Vol. XXXIII, p. 1127) of the capacity of a 40-kv., three-petticoat insulator at about 2×10^{-11} farads, giving a current on a three-phase, 40-kv. system of the order of 2×10^{-4} amperes effective.

Thus by shunting a portion of the high-resistance path of the resultant current through the crossarm and pole to ground, it is seen that an effective current of the order of 3×10^{-4} amperes is obtained through the comparatively low resistance receiver. This means a maximum variation of current, positive to negative, of $2\sqrt{2} \times 3 \times 10^{-4}$ or 8.5×10^{-4} amperes in the complete sine-wave cycle.

Over the perfectly good insulator this current is audible in the telephone receiver as a clear musical tone of the same pitch as the line frequency. If however, there is any defect, such as a crack, or a punctured petticoat, the leakage path is shortened, the capacity is changed, and the volume of sound increased considerably. If the defect is at all serious at the impressed voltage, a brush discharge effect becomes audible in the receiver as a scratching, spitting sound characteristic of such phenomena, before any evidence of it is given to the unaided eye or ear. On an ungrounded delta system, this sound can be heard to fluctuate as the neutral shifts toward or from the wire on the insulator under test.

The range of sound and variations, from the perfect insulator to the dangerously defective one, is very considerable, and capable of being subdivided into many more than four degrees selected, though they seem sufficient for all practical work. If more than one petticoat of a 60,000-volt, four-part insulator is defective, the noise of the brush discharge becomes so intense that it is unmistakable, though perhaps inaudible to the ear alone.

Many curious phenomena will present themselves to the observer who spends any time at this work, which can only be mentioned here, but may be used in further development or use of this same test. For instance, definite knowledge of the exact time of " killing " or " making the line alive " may be had by simply listening in the usual way at the bottom of the pole. Any disturbance on the transmission line is clearly audible in the test set, and the charging of lightning arresters miles away, is heard as distinctly as though near by. If considerable capacity is present on the pole top, through a number of insulators in parallel, an overtone of a very much higher pitch than the fundamental becomes audible, which is probably due to the presence of a higher harmonic.

No difficulty seems to be encountered by various observers in grading the sounds as to leakage indicated, though there may be a difference of one degree set down in the record by different persons when near the dividing line between two degrees. This is dependent on the judgment of the individual, and experience is the most valuable instructor in grading the defects accurately.

Checks of Method

The origination, and institution on the Puget Sound Traction, Light & Power Company lines, of this system of testing, in the spring and summer of 1914, followed a series of particularly severe interruptions to service during the winter of 1913-14, due almost entirely to insulator failures on that portion of the system which had been operating at 60,000 volts for about ten years. The effects of the apparently increasing number of failures were so annoying and cumulatively destructive that some method of locating the dangerous units became imperative. A number of tests were made on the defective insulators with a megger, but no satisfactory results could be obtained as it was necessary to actually find the flaw in the porcelain and then moisten it before any indication of less than infinite resistance could be gotten. A great deal of preliminary experimentation was done with the telephone receiver also, before it was adopted as a routine testing apparatus.

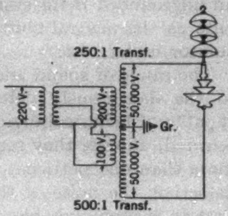

FIG. 3—HIGH-VOLTAGE TEST

As a preliminary check on the accuracy, a pole was selected on one of the lines that had given most trouble during the previous winter, which carried insulators indicating in the test set all three degrees of leakage, as mentioned above. These three insulators were removed from the line and taken to the White River generating station, where a temporary high-voltage test set was rigged up out of the apparatus available. The insulators were kept as nearly as possible in the same condition as on removal from the line, and but a short time, perhaps a couple of hours, elapsed until the high voltage was applied to them.

The apparatus used consisted of a 50,000-volt oil-testing transformer and a 50,000-volt, 100-watt potential transformer connected in series on the high tension side, with the common terminal grounded. The secondary windings were energized from the local 220-volt service and regulation was obtained from the hand induction regulator on the oil-testing transformer.

A new three-part suspension insulator, hung from the ceiling, carried one terminal of the set and the insulator under test was suspended by the pin from this point. To a piece of line wire fastened to the test insulator head with fine copper wire, was carried the other high-tension lead. A diagram of the connections is shown in Fig. 3, and the results of the application of high voltage in Table 1.

TABLE I.

PRELIMINARY HIGH-VOLTAGE TEST AT WHITE RIVER, JULY 1, 1914.

Insulators taken from Pole No. 1739, Tacoma No. 1.

Ins. No.	Tel. test degree leakage	Volts at breakdown from trans. ratio
3a	3	63500
3b	2	84500
1a	1	Did not break down but showed distress at full voltage obtainable.

The maximum e.m.f. obtainable from the induction regulator for the secondaries of the transformer series, was 175 volts, giving 87,500 volts, (trans. ratio 500:1) on the high-tension side; if the effect of a possible phase-angle difference in the two transformers were neglected. While not regarded as a rigid check, this test was considered a practical demonstration of the utility of the telephone receiver for locating defective insulators. It was felt that the argument, that the chosen insulators failed at a voltage at least not any greater than the values given, would hold; and that while further use would give more data, the test would be sufficiently reliable to put into use at once in clearing the transmission lines of the worst cases of defective insulators. A complete test was therefore run on two of the older lines, Tacoma No. 1 and Seattle No. 1, and the poor insulators taken off immediately afterwards.

No other source of e.m.f. higher than 60,000 volts was available in this section, than the rough set-up described above, until the placing in service of the 20 kv-a., 200,000/220-volt testing transformer at the University of Washington, built by Messrs. Dodds & Dashley in 1915. Through the courtesy of Dr. C. E. Magnusson and the University of Washington, the use of this transformer and the facilities of the university laboratory were offered in checking up the results of the test.

A group of insulators, ten in number, was selected from those found leaking in a test with the telephone receiver on the afternoon of February 17, 1916. On February 18th, these were removed from the line, and on February 19th, were transported by automobile to the University of Washington laboratory and tested to complete breakdown. The comparative results of the two tests are given in Table 2. The current to energize the transformer was obtained from an alternating-current generator, whose voltage wave had previously been determined to be very close to the true sine curve. This machine was run by a 10-h.p. motor at a speed giving close to sixty cycles, and the voltage (generator) was controlled by varying the field of the d-c. dynamo used as an exciter for the a-c. generator. E.m.f. was measured from an instrument coil in the low-tension winding of the transformer and the high-tension voltage calculated from the turn ratio (10,000:1). Since the test the high-tension voltage has been checked by means of a sphere gap and found to be about 9200:1 in the neighborhood of 100,000 volts.

TABLE II

COMPARISON OF TESTS

Pole No.	Ins. No.	Tel. Rec. 3/17/16–Test, degree	Breakdown test, U. of W. 3/19/16.				
			Brush discharge		Breakdown		Petticoats punctured
			Volts		Volts		
			Turn ratio	Sphere gap	Turn ratio	Sphere gap	
2645	1	3rd	80,000	73,600	104,000	95,700	1st, 2nd, 3rd
2645	2	3rd	84,000	77,200	96,000	88,400	1st, 2nd, 3rd
2693	1	2nd	100,000	92,000	134,000	123,200	3rd
2693	2	2nd	80,000	73,600	116,000	106,800	4th
2709	3	3rd	80,000	73,600	100,000	92,000	1st, 2nd
2711	2	3rd	76,000	70,000	94,000	86,500	1st, 2nd, 3rd
2717	2	3rd	60,000	55,200	98,000	90,000	1st, 2nd, 3rds
2737	1	2nd	80,000	73,600	104,000	95,000	1st, 2nd, 3rd
2737	2	3rd	50,000	46,000	80,000	73,600	1st, 2nd, 3rd
2759	1	3rd	75,000	69,000	120,000	110,300	1st, 2nd, 3rd

NOTE: Petticoats are numbered from top to bottom. Those not noted as punctured are the only ones over which the flash of power arc was plainly visible at breakdown.

In considering the results of this test and comparing with those of the preliminary check, there are several changes in conditions to be taken into account, chiefly effects due to weather. The insulators removed for the latter were tested during damp weather in the winter time, February, 1916, and in a tide flat location where they were subject to salt water fogs. Two days afterwards they were transferred to a warm, dry laboratory room for the breakdown test. The preliminary test was made on a very warm, fair day in July and high voltage applied to the insulators soon afterwards. The searching out effect of the moisture on the insulator faults in the former case being so much greater in the receiver, a change being made in the observer, and the increasing severity of requirement in grading the leakage, all being taken into consideration, the apparent discrepancy between the two tests does not appear to be so great.

Three important points are to be noted in the results obtained; first, that all, except one, of the insulators rated at second and third degree leakage chosen for the test failed at double the rated insulator voltage (60,000 volts) or less; second, the effect of the location of the punctured petticoats, *i.e.*, whether top, middle or bottom; and third, that every one selected by the test set as of second or third degree leakage shows one or more defective parts. Evident distress, shown by the beginning of the brush discharge, at or near the rated voltage of the insulators should also be noted. If we accept the state law requirements, not one of the entire group would be considered a satisfactory insulator on test, as every one punctured or flashed over at less than two and one-quarter times line voltage.

By scrutiny of the results it is possible to place an approximate upper limit of puncture value for the third-degree leakage insulator near one hundred thousand volts; and a consequent like lower limit for the second degree insulator, though of course in the very nature of the test there is no sharp dividing line between any two consecutive degrees. It was not possible to test insulators of lower than second-degree leakage, on account of the temporary, makeshift nature of the terminals in use at that time on the testing transformer, rendering it impracticable to go above 135,000 volts. The installation of permanent condenser terminals will later render an extension of the check possible. Note should be taken also of the fact that all the second-degree and highest puncture value insulators were those one or more of whose widest flaring petticoats were not punctured, but flashed over. A view of the type of insulator discussed in this test is shown in Fig. 4, cemented on a 2½-in. (10 cm.) galvanized iron pin, as all were.

RESULTS ACCOMPLISHED

As mentioned before, a complete test was made July, 1914, on two of the lines giving most trouble during the winter 1913-14, namely, Seattle No. 1 from Sumner to the city limits of Seattle; and Tacoma No. 1 from Sumner to Tacoma city limits. Only the insulators recorded as third-degree leakage were replaced, although the record is kept for all degrees for further data on the rate of depreciation. In April and May, 1915, a second test was made on these lines, and the third annual test was made in May, 1916. In March, 1915, a test was also made on two pole lines from Sumner to Electron, a distance of eighteen miles. Following is a tabulated summation of above mentioned tests.

TABLE III
SUMMATION OF TESTS

TEST 1914

Line	No. of Ins.	3rd deg.		2nd deg.		1st deg.		Clear	
		No.	Per cent	No.	Per cent	No.	Per cent	No.	Per cent
Tacoma No. 1	1716	100	5.85	155	9.05	216	12.6	1245	72.5
Seattle No. 1	3405	25*	0.735	49	1.44	29	0.89	3302	97.0
TEST 1915									
Seattle No. 1	3405	82	2.4	68	2.0	45	13.2	3210	94.5
Tacoma No. 1	1716	85	4.96	60	3.5	17	1.0	1552	90.2
Elec. No. 1	2670	72	2.7	65	2.42	103	3.86	2430	91.0
Elec. No. 2	2670	224	8.4	75	2.8	105	3.94	2266	85.0
TOTALS									
1914	5121	125	2.44	204	4.0	245	4.8	4547	89
1915	10501	463	4.4	268	2.56	270	2.6	9458	90.2

588 removed from lines.

*First completely tested line.

NOTE: Decrease in first and second-degree insulators in 1915 test was due to skipping poles of lowest leakage in order to locate most defective ones first for removal from line.

A close check on the labor costs of the complete operation of locating and replacing the 85 defective insulators on Tacoma No. 1 on the second test was made, and is here presented.

COST OF TESTING AND REPLACING INSULATORS

Two men testing, 5 days time @ $7.90	$39.50
Number of poles	558
Cost per pole	7.1c.
Number of insulators included in test	1716
Cost per insulator	2.3c
Total number replaced	85
Total cost locating and replacing	$96.35
Cost each	$1.13

Of course as the line insulation becomes better the costs will somewhat decrease, and vice versa, but the average cost of testing runs less than ten cents per pole over all kinds of country, and most insulation conditions on lines in operation.

In conclusion should be given some data on the success attained in the elimination of troubles due to defective insulators, but this material is not in shape just now for presentation in definite form. The fact stands forth, however, that whereas in 1914 any ground on the system, arcing or otherwise, resulted in numerous insulator failures, burning off poles and crossarms, and even burning through No. 0000 copper line wires on the lines mentioned above; since that time there have been only two cases of destructive insulator breakdown on these lines. The first one of these was on Thanksgiving Day, 1915, and was apparently due to a direct stroke of lightning, which stripped every bit of porcelain out of a three-disk, dead-end insulator on a river crossing tower at Orting on Electron No. 1 Line, leaving the pole top wire connected directly to the pole by the inter-linking hardware; and broke down a pin-type insulator on the same wire four miles north of Orting, literally blowing the top of the insulator clear of the pin. Despite the fact that one line wire between Renton and Kent lay on the ground for some time until burned off above arcing distance, no other insulators on the tested line failed under the severe strain, although on other lines not tested quite a number did. The second case of failure was February 2, 1916, on Tacoma No. 1, during the very severe sleet storm of that period and was caused by trees growing near the line bending over under the sleet load and grounding one wire numerous times at short intervals. It is also to be taken into account that the last two years have been a period of more severe storms, especially of lightning and sleet, than have been known in this district for many years.

Depreciation Data

Some effort is being made to collect data on the rate of depreciation of porcelain insulators through annual tests over the same lines, but completeness along this line will require more time and more standardized methods than have been used in the past. Considerable study and latitude in reasoning are necessary to correct interpretation of the records obtained in order to get a clear idea of the facts as to the rate of depreciation. For instance, the testing so far in this work has been done with the sole idea in mind of locating the *worst* insulators and improving the line insulation at once by their removal, so that very little attention has been paid to those of second-degree leakage or less, and the records of them are not complete or exact. Another factor for which considerable allowance must be made is the personal equation of the observer, who in some cases is very liable to miss the indications of lower leakage, either intentionally as intimated above, or due to lack of keenness of observation. Then too, there is considerable chance for confusion of circuits of the leakage current, that is to say, if a pole top holds one very bad insulator, there may be some indication of leakage from the other ones, though the latter will show up as perfectly sound upon removal of the defective unit. All of these things are brought out in the accompanying depreciation list, which contains the results from three tests over the same line, each one being made by a different man, without any record of the previous survey.

TABLE IV

DEPRECIATION LIST TACOMA NO. 1 LINE

Tested	July, 1914			May, 1915			May, 1916		
Insulator Numbers	1	2	3	1	2	3	1	2	3
Pole Nos.									
2137	1	1	1	0	3*	0	1	1	3
2231	1	1	0	0	2	2	1	2	3
2333	1	1	1		Clear		1	3	3
2499	1	1	0	1	3*	0	1	0	1
2587	2	0	1				3	3	1
2609	3*	0	1	0	2	3*	0	0	0
2657	1	1	0	3*	3*	3*	0	0	0
2671	0	1	0	3*	3*	3*	0	0	0
2699	1	2	0	2*	3*	3*	0	0	0
2723	1	1	1	3*	3*	3*	0	0	0
2753	3*	1	1				0	2	1
2789	2	2	3*	3*	3*	0	0	0	0
2793	0	3*	0				3	0	3
2827	3*	3*	3*	0	0	0	0	0	0

*Insulators replaced immediately after the test was completed.

Pole No. 2137 serves as a good illustration of several of the points stated above. The first test, July, 1914, was made with more care than that of May, 1915, the lower leakage consequently being noted. In the latter test the depreciation and excessive leakage of insulator No. 2 so overshadowed that of the other two in the hearing of the observer, that, coupled with the main idea of locating the bad insulators only, the result was a record of zero leakage for insulators Nos. 1 and 3, although careful attention would probably have also designated them. The third test, May, 1916, after the replacement of No. 2 insulator, shows what is probably the effect of a confusion of the circuits, as it is conceivable that a portion at least of the leakage current from No. 3 insulator would flow along or through the crossarm to the pole, up the pole top to the receiver terminal and back through the receivers to the pole at a lower point.

Poles Nos. 2609 to 2827 show very clearly the improvement in insulation and the clearing up of the line from the replacement of the third-degree insulators, whether singly or all three on the pole top. No. 2753 exemplifies the perfect insulation of insulator No. 1 two years after the replacement of a defective one, and the gradual depreciation of the other two. No. 2793 is a like example, but with much more rapid depreciation of the clear ones. No. 2789 shows the increase to third-degree leakage from second in less than a year's time and the subsequent clear test a year after replacement. This table will give some idea of the method for studying the depreciation rate which is being planned on for the future.

DISCUSSION ON "TESTING FOR DEFECTIVE INSULATORS ON HIGH-TENSION TRANSMISSION LINES" (FLAHERTY), SEATTLE, WASH., SEPTEMBER 6, 1916.

Harris J. Ryan: The purpose of the author is primarily to lessen the operating troubles that are caused by the deterioration of insulators. The elimination of the deterioration of insulators will require much effort and time, and until it is accomplished, the transmission engineer must value highly a method that enables him to have a defective insulator located before it causes an interruption. In the meantime he has an intense interest in the discovery of the causes of such deterioration and their avoidance. Doubtless some deterioration of porcelain high-voltage line insulators may be due to defects in design or construction, though from the evidences at hand most of the deterioration that is going on is due to defective porcelain. From the ceramist we learn that it is difficult to make electrical porcelain which is altogether non-porous, and from the geologist, that earth products to be mechanically strong and durable under the action of the elements, must be highly refractory and impervious to moisture. In one instance the deterioration of more than a thousand suspension insulator units manufactured eight years ago was one and a half per cent for their first six and one half years of service on a 100-kv. line. In another case more than a thousand units were bought and stored in the open four years ago. By tests made on them during the past summer, five per cent were found by the megger to have failed, and fifteen per cent failed to withstand the one-minute flash-over potential test. It is reasonably certain that design and construction can account for but a small portion of the great difference in the number of failures that occurred in these two lots of insulators. It is also reasonably certain that the denser structure of the porcelain in the older insulator was largely responsible for their few failures.

Finally it appears that if such a material as fused quartz could be cast into insulator forms, a decided improvement in insulator practise should result. Fused quartz is a thoroughly vitrified material that is dense, tough and refractory, requiring no annealing.

L. T. Merwin: I would like to commend for experimentation a method that might lead to results possibly cheaper in some instances than this method outlined in the paper. A year ago I had occasion, in experimenting with a wireless receiving set which, as some of you know, we use regularly as a means of dispatching on our transmission line between the City of Portland and the power station on the White Salmon River, to find out whether it would have any application to the discovery of weak insulators. We noticed that intermittent discharges were coming in, that could not be attributed to any nearby wireless station. We believed that some of them came from defective insulators, and further tests proved that to be the fact. I have not had the time to continue the experiments, and I simply offer them for what I believe to be a very profitable line of experimentation. It is as follows: Take an ordinary audion receiver set of the De Forrest pattern, with a high resistance head set, and if the line is along a highway sit in your car with a wire fastened to a bamboo pole, say, of six or eight feet in length, with the bulb ready for action and the receivers at your ears. Drive along, and, as you do so, you will hear the characteristic hum of the transmission frequency with its harmonics, and if you pass any insulators that are defective in such a way that transient discharges are taking place, you will hear the characteristic scratch. I have not carried the experiment far enough to know how conclusive the determinations are, but when driving along a line at the rate of 15 miles an hour, you would not fail to hear any oscillatory discharge in an insulator. It would certainly be a much more rapid means of discovering broken down insulators than any other. Now, having once discovered a pole with a broken down insulator, whether the means that I am mentioning will be effective in definitely locating which insulator it is, I do not know. I talked with Mr. Crawford last year about it, and it is quite possible that he has made some experiments with this method. Whether it will be effective in finding defective insulators on steel tower lines, I do not know, but I belive it is a means that is well worth investigation. I might mention one little instance that came up in my experiment: In driving along at a rate of approximately 15 miles, I heard the scratch, and stopped the machine and got out to locate, as nearly as I could, the pole that had the defective insulator. By moving the antenna wire, which we will call this little wire fastened to the eight-foot pole, back and forth, I finally located the trouble on an adjacent power system some four blocks away, so I do believe that the method has merit.

E. A. Loew: Notwithstanding the fact that all insulators are reputed to be more or less "rotten," it is, nevetheless, evident that if the power companies are to continue to transmit power at all, until better insulators have been designed and manufactured, they will have to continue to use those which are now on the market, and, therefore, it seems to me that some method of testing insulators which are in use, while they are in use, is of exceedingly great value to the power companies, expecially if that method is a simple one. Therefore, in reading over Mr. Flaherty's paper, I have been impressed with the idea that some such method of conveniently testing insulators in service as therein described, is the kind of insulator test which operating companies have long needed. So far as insulator testing is concerned, there are two distinct circumstances under which tests are desired: First, there is the demand for a factory test or series of tests, which are made before insulators are accepted and installed by the purchasing company, in order to insure the delivery of units which will meet such specifications as are suited to the service for which the insulators are intended; secondly, there is the demand for tests on the installed insulators at regular intervals while they are in service, that is, without the expense and interruptions incident to their removal from the line, in order to determine the condition of insulators from time to time so that those which have developed defects and are liable to cause trouble may be detected and replaced by new ones before the trouble develops. As already pointed out by Mr. Flaherty, the first mentioned class of tests have in the past been the subject of considerable discussion and are now pretty well standardized. The methods there developed, however, have not been suitable to the testing of insulators under ordinary service conditions. The method outlined in Mr. Flaherty's paper and now in use by the Puget Sound Traction Light and Power Company on its lines is, so far as I know, the first method proposed by which a fairly reliable test of the serviceability of an installed insulator may be quickly and conveniently determined. Its simplicity and cheapness, accompanied by a fair degree of reliability will, no doubt, recommend this method, or some modification of it, to power companies generally, where a rough qualitative test of this kind is required. A modification of this method of testing, which seems to me to be highly desirable, is some arrangement whereby the personal equation of the operator may be either largely or wholly eliminated. How this test may best be brought about I am not prepared to say. Some of the obvious advantages of making qualitative tests of this kind on insulators in service may be enumerated as follows: First, the test may safely be made while the line is in service; it is a simple test easily made by the regular line force at a small cost, and it apparently gives indications which are sufficiently reliable for practical purposes. Secondly, by means of such tests made at regular intervals, line trouble is anticipated and thus often prevented. The loss resulting from damaged apparatus and shut-down should thus be greatly reduced. Thirdly, by keeping a suitable record from month to month, and from year to year, the points of greatest depreciation of line insulators and of greatest line trouble may be more definitely located. By increasing the insulation on such parts of the line, trouble should be further reduced, continuity of service better guaranteed and greater reliability of operation secured.

J. B. Taylor: If material that is weak, or has already partially failed, can be located and replaced before complete failure occurs, records for uninterrupted service may be improved. Mr. Flaherty's method for weeding out defective line insulators, using a telephone receiver to detect small leakage currents, is novel and worthy of extended cautious trial. Work among live 60,000-volt conductors with exploring wire in hand and testing circuit connected to head and feet calls for caution.

As described, the field for the method seems restricted to wooden poles with pin-type or single-unit insulators, though the author intimates that some study has been given the case of steel towers and chains of suspension insulator units.

No figures are given for break-down of insulators taken at random from the same line and giving zero indication in the telephone. If these can be added, the value of the telephone method may be made more convincing.

In Table IV the records of certain selected poles for three consecutive years are discussed as showing progressive increase in degree of leakage. This deduction may be questioned on the showing of Table III, where for example Tacoma Line No. 1 lists 371 first and second-degree insulators left on the line after 1914 test, though only 162 of all three grades are found on the same line in 1915 test. Data for the test in May of this year are not given.

Incidentally it appears more probable that the "clear musical tone" heard when testing a perfect insulator is of higher frequency than fundamental (assumed to be 60 cycles). Not only does the capacity connection favor the harmonics, but telephone receiver sensibility is relatively low at commercial frequencies. (See A. I. E. E. TRANS. XXVIII, 1909, page 1184)

C. E. Magnusson: Mr. Merwin's use of the audion is merely a method of magnifying the effect of the electromagnetic waves as they radiate from the damaged insulator. I would raise the question as to why the insulators are left so long on the line in a damaged condition. From the paper, I would judge that the operators take a keen delight in edging up as close as possible to the break-down point. It would appear as a more desirable plan to eliminate defective insulators before they reach the fourth stage, and thereby save the additional loss that necessarily follows when the break-down actually takes place. I understand that the continuity of service record for the P. S. T. L. & P. Co., has been vastly improved since the method described in Mr. Flaherty's paper was adopted, and if I understand correctly, the engineers in charge could guarantee uninterrupted operation if the insulators of the third degree or second degree were to be taken out, so that they would not have to wait until the insulators were so near the breakdown stage. I would like to ask Prof. Ryan this question: From his remarks, may we hope that some day, we shall have quartz insulators?

H. J. Ryan: We hope so. I have no other foundation for expressing that hope than that quartz has splendid qualities which render it adaptable for the purpose. There are quartz utensils made for the chemical laboratories, as we all know, that are not prohibitive in price, notwithstanding the fact that the laboratories do not use a great deal of product of that sort, and it would seem that if the matter were gone at in a large way, because of the fact that silica is a very abundant material in nature, it should be practicable to have quartz insulators.

M. T. Crawford: I would like to say just one word in defense of Mr. Flaherty's paper, after thinking over Mr. Buck's remarks this morning. Mr. Buck made a very good point, in stating that the insulation of our systems was poor, and that redesigning should be given attention, and replacement taken care of. But the re-designing of insulators is going to take considerable time and the replacement outright of many thousand of more or less defective insulators is going to take a sum of money which cannot be always obtained promptly. In the meantime, the system must be operated, and I believe the engineer is doing a real service when he takes what is available and makes it work, securing thereby reasonably good service from poor equipment, while the process of redesigning and replacement of equipment is in progress. I have received a great many letters from all over the country since this method was first brought out two years ago, inquiring for additional information, describing the results of using the method; and while in some cases, local conditions prevented its successful use, there have been a great many systems that have made very good practical use of this method, and reported good results. In our own systems, we have almost no trouble from interruption of service due to defective insulators, whereas, three years ago, it was one of our main sources of trouble.

W. D. Peaslee: I think that one point raised by Prof. Magnusson—that is, as to leaving slightly defective insulators in service—is simply a question of economy. The progressive deterioration of an insulator as it goes to No. 3 is very apparent. We all know that if we have a pole in a transimission line that begins to rot, we don't take the pole down at the first splinter of rot that appears in it, but we watch that pole very closely, and as it gradually deteriorates toward a condition of worthlessness, we remove it. I think the same rule applies to insulators. Mr. Flaherty has described a method whereby it is possible, at very reasonable expense to watch these individual insulators, and if an insulator is shown to be defective on No. 1 test, that is no reason for taking it off the line, because that costs money, and money has to be borrowed, and it is not always easy to get. Whereas, if we can go out and watch that insulator, and it gradually goes to No. 2 we can note it in our book. Then if it goes to No. 3, we can take it out, and in the meantime we have had probably two years use of that insulator. We have to face the fact that no matter how good an insulator is when we put it on the line, it has to be replaced sooner or later. Insulators will deteriorate, and the thing for the engineer to do is to take off the constantly deteriorating factor in his transmission line. I have taken off an insulator that has failed, and outside of the points of failure, the insulator was good; the porcelain was good. It was as good as you could expect, under present conditions, to be manufactured. There was no reason to suspect that that insulator when it went on the line, was not good, and gradually deteriorated, and I think that the practise of leaving these insulators on until the last moment is pretty good, economic engineering.

R. W. Pope: The old Boston and Albany line was insulated with what my brother called white flint insulators, and he considered those insulators very much better than glass. That was as far back as '58. They were abandoned I believe because glass was cheaper and served the purpose. I have never seen any reference to that material, but I remember how those insulators looked at that time, and I have had an idea that they might have been quartz, and their manufacture a lost art.

C. P. Osborne: I might say that we have just completed a test on our power line, equipped with suspension type insulators. Last year we made no changes in those insulators. Two years ago, we removed all insulators that tested less than 2000 megohms. Last year we made the megger test, and we found about 4 per cent of those insulators that would test below 2000 megohms and after discussing the proposition, we decided to let them go over and see what the result would be, without making any change. We did so, and had no failures at all. The test that has just been completed shows 15 per cent that tested below 1000 megohms. We have had no failures yet. We expect to change insulators this year. When the line was built, five years ago, we had considerable trouble. We had 14 shut-downs in six months from insulators breaking down. Three years ago we installed 12 insulators on the platform, six in a string, and on one of the strings, we put a 600-pound weight, and the other was without weight. The object of doing that was to determine if our trouble was mechanical. Those 12 insulators have been hanging there in the weather three years, and we have come to the conclusion that the electrical stress is what has been breaking down the insulators. We have no reason for believing that, except from our own observation.

The great objection we find, in testing with the megger is where you have a ground on the line, as we have in our tower line, there is one insulator that you can't test unless you disconnect it from the tower. Three months ago, we tested five miles of the line, and the test we just completed checked almost exactly with the test that was made three months ago. Some of them showed a little bit lower, but not very much. We are going to try to see if we can get the same results on the steel tower line. We may be able to do that on our wood pole line, but hardly on the steel tower line. We also have a line that we have been carrying 60,000 volts on for four years, and we have only had one insulator breakdown. You can walk along that line at night and see the fireworks almost any place. You don't need a telephone receiver to find those.

George Harding: It has been stated that porosity is probably the cause of the breaking down of the insulators. I would like ask whether or not this has been tried: It has been stated that you can expel the moisture by baking the insulator. Has this experiment ever been tried: Immersing the insulator, after the moisture has been expelled, in oil? In other words, impregnating the insulator with oil, and then putting it under the test.

H. J. Ryan: That idea occurred to some of the engineers of the power companies with whom we worked this summer. We have not, however, made any effort to carry out an undertaking such as you have suggested. Naturally, since porosity seems to be such an evil, impregnation with parffine or oil, or some other similar material was brought forward. However, there are so many evidences that a unit that you can treat in such fashion, and that you can make work very well for a time, when you leave it, and have forgotten it, in four or five years, the oil would go out of it, and it would again be in a bad class. A word of comment on one point that was brought out by Mr. Osborne, and that is in regard to the voltage duty that a defective unit will carry in a suspension insulator. You have spoken of units that are continued in service when they have a resistance of 1000 megohms. Surely, such units are capable of carrying a lot of duty—normal voltage duty. Mr. Osborne felt that they would like very much to know the capability of defective units in regard to voltage duty, and the voltage duty that they would carry or fail to carry in a string. So, in our laboratory, with a high-voltage potentiometer, we erected strings with as many as 12 units, and applied 75,000 volts to ground thereon. We employed, first of all, good units throughout, and then employed a bad unit or two bad units next to the line, and then employed a good unit mounted next to the line, and then a bad unit or two bad units, or arranged them in various other combinations that, of course, immediately suggest themselves to the mind. The bad units had been shorted through, were punctured, or they were units that were water-logged. In a string of 12 units, for example, each unit carrying an average of 8.3 per cent of the total, units would carry as much as six or seven per cent that had actually been shorted through on high-voltage tests, because they were defective and conductive. Nevertheless, it appears to me that units of that kind in a string would surely fail under the ordinary forms of high voltage. It seems to me that the danger from leaving units on a line, that show as low a resistivity as 1000 megohms, comes from the fact that one is manifestly leaving on a line an insulator that is pretty porous, and is engaging in a process of absorbing more and more water all the while. It must have absorbed quite a little, apparently, in order to be down so low. As long as certain accidental forces don't come along, laboratory studies indicate that those units will carry very nearly as much duty as if they were in perfect condition, thus not throwing an undue amount of duty on to the other units.

C. P. Osborne: I would like to cite one instance which happened last Saturday on our line. The Southern Pacific has a tap from one of our substations which operates their line. The lightning struck their line, burning the tie-wire off the insulator going to the ground plate on the pole, which the Commission, I believe, makes it necessary to install. That, no doubt, created some disturbance on that line. Now, the tower line which I spoke of, kicked out at the generating plant, at least thirty miles from that point. When I mention the insulators being 1000 megohms, I will state that we have three strings, and all of them showed 1000 megohms. This simply shows that here is a case where lightning did strike the line, and there is no question but what some undue strain was put on that line by the lightning striking it. It also burned up some of the instruments in the substation, right along side the line. We have been a litle bit skeptical in making the tests. As we look at it now, it is a case where we have to go through every two years and weed out the bad insulators, and put in new ones, and that is going to continue until we get better insulators. Were those insulators Mr. Pope spoke of, bullet proof?

R. W. Pope: The form I speak of was pretty nearly bullet proof, because bullets glanced off from them.

B. G. Flaherty: All our lines here have ungrounded neutrals. We have had no experience with the grounded neutral systems. In reply to Mr. Merwin's suggestion as to the audion testing set. We can use the telephone receiver in practically the same manner except that a grounded terminal is necessary—the same bamboo pole and the antenna. You can ride along the line and get practically the same results with just the telephone receiver alone. An incident comes to my mind where we were testing a line this summer. The linemen were testing the insulators on a pole line with a steel tower line paralleling it. They called my attention to two cases where the tower line had defective insulation on it, that they had discovered by walking along with the pole over their shoulder. Mr. Osborne, undoubtedly a number of your poles or towers would have no defective units on them.

C. P. Osborne: There are a lot of them that have no defective insulators on them.

B. G. Flaherty: That would avoid your going over them with the megger test, if you could locate the poles or towers with the telephone receiver set.

C. P. Osborne: Have you tried that method at all with lines with grounded neutrals? We operate a grounded neutral on all 60,000-volt lines.

B. G. Flaherty: No. We have no grounded neutrals here. As to Mr. Osborne's statement about the 45,000-volt insulators, and the ability to use the telephone receiver set, we have about 25 miles of line with 30,000-volt insulators, that we have tested. An old style insulator was put on, and it has been on a number of years. Our telephone receiver set seems to work all right in those cases. Of course, we get an excessive amount of noise, and it is not necessary to make contact with the pin on the insulator.

The lineman, in testing, simply starts out along the cross-arm and observes by the comparative intensity of the sound, and he can tell those insulators that are most defective.

Mr. Taylor referred to the discrepancy in the tables given, as to the number of insulators in the different tests, giving a larger number of the lower degree leakage in the first test of July, 1914. I have explained in the paper, that we were very much more careful in the first tests in 1914 to get the degrees of leakage. As a matter of fact, we almost neglected the lower degrees in the tests of 1915 and 1916 as the sole object of the test was to locate the dangerously defective units.

S. C. Lindsay: The insulators, Mr. Flaherty referred to as "30,000-volt insulators", were not designed for that voltage. They were designed for 55,000 volts and were first used on a 30,000-volt line with the idea of later changing the line to 55,000 volts, and in that way became known as 30,000-volt insulators. They are very much smaller than the 55,000-volt insulators used at this time, and although we used them for a short time at 55,000 volts, we found that they were an unsafe insulator for that voltage.

J. P. Jollyman and J. Mini, Jr.: Regarding the use of the telephone receiver for the detection of defective pin-type insulators on pole lines, the writers after the publication of Mr. Crawford's outline on this subject of August, 1914, gave the method, what they believe a fair trial. First in an experimental way as will be described later, and finally by actual application to several sections of existing 60-kv. lines on the Pacific Gas and Electric Co.'s system.

About this time it was decided that parts of several lines would be rebuilt for various reasons; this required the insulators to be completely removed from the poles during the reconstruction. This opportunity was taken advantage of and a number of "telephone surveys" were made of the same pieces of line, at different times of same day, and also on different days, by two independent men, who took new records on each survey, without reference to results of previous surveys or of each other's work. Here the first points against the telephone method showed up, in that records for the same pole often were far divergent for the several tests, while the voltage and load conditions of the circuit remained practically uniform.

In all but two cases, the lines carried 14-in. diameter tops 4-part pin-type insulators, and the poles and insulators as regards, spread, etc., were about the same as exist on the system on which Mr. Flaherty conducted his tests. The only point of difference of which we know is that his system operates with isolated neutral while our tests were on the solidly grounded neutral system. The comparison of climatic conditions also is not known.

As the insulators were removed from the poles they were carefully tagged and hauled to a central point, where each shell of each individual assembled insulator was given a careful test with the megger, and then by the application of 55 kv. from a 2000-watt testing transformer across each separate shell.

Referring to Fig. 3 and to the note under Table II of the paper, it is understood that the voltage tests were made by applying the test terminals to the shells over all. Owing to the relative lengths of striking distances due to design of certain insulators, this method of detecting punctured shells, is very often not reliable, since the spark will sometimes jump across two shells from the pin for instance, rather than jump down along one side of a long inner shell and out and up again on the opposite side of this shell. This leads one to believe that a shell was not punctured. This "over all" testing throws unbalanced stress on the inner shells as a rule (depending of course on the design), and often punctures them on a total test of say 110,000 whereas they will often stand 60 to 70 thousand volts or perhaps flash-over, if tested individually. It is perhaps (especially in making checks on the phone test), more proper to find what shells are already cracked, punctured, or so porous and full of moisture as to stand practically no voltage, rather than to puncture some of them at 50,000 volts per shell or over. An insulator having four such shells standing such a voltage per shell, would be expected and has proven in many cases to still be capable of giving considerable service, and it is doubtful if any phenomena it exhibits under normal operation, would give any phone detection and therefore should not be counted as a debit or a credit to the number the phone missed, or on the other hand detected.

Experimentally, various types and sizes were put on a pole on which the circuit connecting thereto, could be switched on or off at will. It was soon discovered that it was not necessary to connect one terminal to the pole, but that a regular wireless effect existed and an antennae held up brought the same results. Sound, four part insulators, every shell of which has passed a megger and severe voltage test, were put on the pole. One shell after another was shunted out by a wire, and the result in the phone receivers was an increasing disturbance after each such artificial shorting out of shells. Carrying out this procedure in the reverse order, the noise produced by the insulators became quieter, returning to the clear hum again as the short-circuiting wires were removed from across the shells. Again other sound insulators were dusted over and then sprayed with water from an atomizer; these got noisy but gradually returned to quiet again as the sun dried them off. The receivers used were of the wireless type, two of them having a resistance of 2000 ohms, and one set, 3000 ohms per pair. These different insulators of various degrees of defectiveness purposely put on the test pole, together with those temporarily made defective by artificial means as noted above, gave quite similar disturbing noises in the receivers. These tests gave the field men "ear training" before they actually did any testing on existing lines in regular operation. Various degrees of noises were found characteristic upon which the field men standardized for record purposes by coining describing words, such as: "light, medium, and heavy fry; light, medium and heavy continuous bombardment. Numerous attempts were made to locate the particular defective insulator purposely placed on the test pole, from the three total using the scheme outlined in Mr. Crawfords' paper, but with very little success. The nearest approach toward picking the correct defective insulator was perhaps by the use of a telephone transmitter, mounted on the end of a long light pole, by which it was held up close to the end of the insulator pin of the several insulators on the pole. The other end of the wire telephone circuit (including dry batteries and ordinary telephone receiver) was held by a man standing on a well insulated stool, located at the base of the pole. The scheme is dangerous and the results far from reliable as the number of incorrect detections far outnumbered the correct ones. It might be stated that whether the three metallic pins located at the two ends of the cross arm and at the pole top, were connected metalically or not, did not seem to effect the phone test results.

Tests made on lines in regular operation.

Test No. 1

Each pole carried three 3-part 14-in. diameter insulators. Location about 90 miles inland from sea coast. Weather dry and relative humidity fairly low.

9 poles selected (which gave three consecutive checks on telephone survey) from out of a total of about 50.

Poles	Character of phone test.	Megger and high-voltage test of each separate shell of all insulators on pole.
2	Clear hum	O. K.
7	Medium to heavy bombardment.	At least one shell in one or more insulators of each pole group (3 insulators) found defective.

The phone test was checked correctly by megger and voltage tests on the insulators of all 9 poles, or 100 per cent.

It might be added that in the above, the tests were made with an antennae length of the phone circuit not over ten feet above the ground, same having a sharp point which was lightly driven into the pole butt. If the end of the antennae is held up near the cross arm, all the poles on this line give the "fry" sound in the receiver. Each shell of this type of insulator is of course carrying more voltage stress than the shells in other types of insulators used on the lines, where the remaining tests were conducted.

Test No. 2

Three 4-part 14-in. diameter insulators per pole.

Location about 40 miles inland from sea coast.

17 poles selected at random.

Phone test clear	Phone test clear	Phone test bombardment	Phone test bombardment
Insulators found O. K. by megger and voltage test.	Insulators found defective by megger and voltage test.	Insulators found O. K. by megger and voltage test.	Insulators found defective by megger and voltage test.
0 poles	6 poles	5 poles	6 poles

Total phone tests which were checked correctly by other tests.............................. 6 = 35 per cent

Total phone tests which were not checked correctly by other tests.............................. 11 = 65 per cent

TEST NO. 3

Three 4-part 14-in. diameter insulators per pole.

Location about 20 miles inland from San Francisco Bay.

25 poles selected at random.

Phone test clear	Phone test clear	Phone test bombardment	Phone test bombardment
Insulators found O. K. by megger and voltage test	One or more shells of one or more insulators found defective by megger or voltage test.	All insulators tested O. K. by megger and voltage tests.	One or more shells of one or more insulators found defective by megger or voltage tests.
2 poles	0 poles	16 poles	7 poles

Total phone tests which were checked correctly by other tests.............................. 9 = 36 per cent

Total phone tests which were not checked correctly by other tests.............................. 16 = 64 per cent

TEST NO. 4

Six 4-part 14-in. diameter insulators per pole. (Twin three-phase circuits on a single-pole line, with the two circuits solidly connected in parallel at both ends.)

Location about 20 miles inland north of San Francisco bay.

209 poles tested; consisting of two pieces of line about 8 miles apart and of 70 and 139 poles respectively.

Phone test clear	Phone test clear	Phone test bombardment	Phone test bombardment
All shells of all insulators found O. K. by megger and voltage test.	One or more shells of one or more insulators found defective by megger and voltage test.	All shells of all insulators found O. K. by megger and voltage test.	One or more shells of one or more insulators found defective by megger and voltage tests.
48 poles	50 poles	46 poles	65 poles

Total phone tests checked by other tests........... 113 = 54 per cent

Total phone tests not checked by other tests....... 96 = 46 per cent

TEST No. 5

Three 4-part 16-in. diameter insulators per pole.
Location about 3 miles inland from San Francisco bay.
81 poles tested, all in a single continuous piece of line.

Phone test O. K. Insulators O. K.	Phone test O. K. Insulators Some shell defective on one or more insulators.	Phone test bombardment Insulators O. K.	Phone test bombardment Insulators Some shell defective on one or more insulators.
9 poles	8 poles	12 poles	52 poles

Total poles on which phone test was checked by other tests	61 = 76 per cent
Total poles on which phone test was not checked by other tests	20 = 24 per cent

The results show that a number of defective insulators can be detected and removed as a result of the phone test but at the great expense of taking down many times the number of sound insulators from the poles showing defective in order to get the few bad ones. Again, the expense of taking down the insulators from poles showing defective, only to find that no bad ones exist. And lastly perhaps the most unfavorable feature—trial tests demonstrate a large percentage of defective insulators are missed altogether in the field survey. While the probability of future line trouble is no doubt decreased in direct proportion to the number of defective insulators removed, it was this last feature which led to the abandonment of the telephone method for the trial of other schemes which it is hoped will show more perfect scores in the results obtained.

Current audible as a clear musical tone over good insulators is the same as that obtained by antennae effect in the vicinity of the circuit and is due to harmonics, since the fundamental at 60 cycles is a very low pitch tone too low to be at all noticeable in the telephone receivers. In a system with a grounded neutral the principal harmonic is usually the third and in a delta system the fifth or seventh.

We agree that brush discharge is the cause of the scratching or spitting noises heard as superimposed on the "clear" hum. Brush discharge is not necessarily due to a cracked shell or a shell of low megohm resistance. If the design of the insulator is such that the air is overstressed at any point, a brush discharge will be formed even though the insulator is perfectly good. A certain type of insulator with which we have experimented, all showed "bad" on the line but were found "good" when removed and tested.

We do not think that the neutral of an ungrounded delta system of any size and voltage shifts sufficiently to affect the voltage over the insulator on any one phase unless an actual ground has taken place. The displacement of the neutral can only be caused by the flow of a very considerable current to earth from one phase. The current which must flow to ground from one phase of a delta system to shift the neutral to that phase is equal to about 1.5 times the normal charging current. This current to ground would be about 18 times 1.5 or 27 amperes on a 60-kv. system with 100 miles of line. Certainly no current which would leak over one or several insulators would shift the neutral enough to affect the voltage over the insulators on that phase.

We suspect that the air in the vicinity of the second (short) shell of the insulator would become overstressed if the top was defective and frequently overstressed if the third or center was defective. This particular type of insulator appears to be one which lends itself very well to the application of the method of testing described. It should not be inferred that the method will be equally successful with other types of insulators or under the conditions existing on other systems.

E. E. F. Creighton: An experimental and theoretical study was made of the telephone method of testing insulators in an endeavor to bring out definite information on the factors involved and to determine the limitation of its successful use. The experimental work may be divided into two categories: namely, first, tests with gaps and resistance; and second, tests on defective insulators.

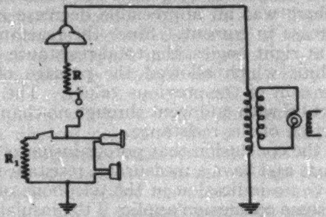

Fig. 1

The apparatus for the experimental work (Fig. 1) consisted of a sine-wave alternator with a smooth core; a 50-kv. step-up transformer, three good suspension disks and seven defective pin-type insulators, a small sphere gap (2.5 cm. diameter), a water resistance tube giving a resistance of 60 megohms, telephone receivers (one of 5-ohms resistance and one of 70-ohms resistance), and a resistance box for shunting these telephones. The studies made can be designated under five categories:

1st, determine the point of brush discharge in the insulator when there is neither series resistance nor series gap in the circuit; 2nd, determine the effect of series resistance in diminishing the sound in the telephone receiver when there is no gap in series; 3rd, determine the effect in the receiver of introducing a continuously increasing series gap when there is series resistance in the circuit, and 4th, the same with no series resistance in the circuit; 5th, determine how much shunting resistance in parallel with the telephone receiver becomes undesirable.

TEST WITH GOOD INSULATORS IN SERIES

No attempt will be made to present the tests in detail but rather to give the deductions made from these tests, which will be designated as *A*, *B*, *C*, *D*, and *E*.

Conclusion A. When there is no gap in series with the insulator and the charging current of a single suspension disk insulator is carried through the telephone a pure sine wave gives a low, musical note. With a difference in sensibility of the telephone receiver and difference in attention the 60-cycle note becomes audible for different values of current. In a noisy room with a 70-ohm receiver in series with a single 10-in. suspension disk the sound becomes audible at 20 kv. applied. Since the capacitance of a single disk is about 34 times 10^{-12} farad, its reactance will be 85 megohms, and the current in the receiver 236 micro-amperes.

When the resistance of 68 megohms was placed in series with the insulator there was an appreciable decrease in the sound, due to the decrease in current. Since the reactance and resistance combine at right angles, the total resistance in the circuit was 110 megohms which allowed the passage of 182 micro-amperes (77 per cent of the previous value). The musical note was pure to start off with and went through no changes in timbre by the introduction of the resistance.

This leads to the conclusion that porous insulators which have absorbed moisture and have a measurable resistance in megohms or lower will give no indication in the telephone of their defectiveness. The same conclusion applies if the insulator is cracked and filled with moisture which makes a moisture contact with the cement. If the contact between the cement and the crack is made by means of a small spark, then the conditions are different and a discussion will follow under a later paragraph.

Conclusion B. By gradually raising the voltage on the suspension disk from 20 kv. the growth of the brush discharge in the insulator can be heard in the telephone. The brush discharge is also audible directly from the insulator. At 50 kv. there is considerable roughness in the musical note which can be attributed to the brush discharge from the various points on the surface of the Portland cement in the head of the insulator. Once familiar with this sound of the uniformly distributed brush discharge it can be distinguished from the other sounds which will be described later. This sound is somewhat diminished by the introduction of 68 megohms in series with the suspension disk.

Conclusion C. If the resistance is left in series and the voltage is maintained constant, say at 50 kv. and the sphere gap is gradually opened, a new sound of rather high pitch but not a musical note takes place. As the gap is gradually opened to 0.02 in. the pitch gradually decreases and the intensity of sound increases. Beyond this gap length the sound takes on gradually a different note. The sounds are full of different noises which gradually grow and fade in a way which baffles description in words. At small gaps there is a hissing noise like the escape of steam. As the gap increases there is superposed a disagreeable muscial note of decreasing pitch. Then there appears a rumble like the sound given off from the rails by a rapidly moving express train. This gradually passes into a disagreeable scratchy sound and at the larger gaps ending up with a distinct rattling sound as the sparks become less and less frequent per second. From the smallest gap to the largest gap the intensity of the noise, irrespective of its character, gradually increases, so long as the series resistance is left in place. The difference between the sound given out by the series spark and the sine wave current without series spark may be described as the difference between a noise and a musical note. It is just as distinct as the difference between multiple strokes on a bell and multiple strokes on the bottom of a dish-pan.

We may conclude from this that any spark in an insulator with the resistance of a wooden pole in series will cause a peculiar sound in the telephone receiver, the nature of the sound depending on the length of the spark in the insulator. If a single skirt of a pin-type insulator is cracked and the charging current is sparking into this crack, the sound will be distinctly heard on the telephone and it will have a note that can be distinguished from both the musical note and the evenly distributed brush discharges. The telephone receiver then is fitted to detect this kind of a fault in an insulator but the voltage must be such as to cause the spark. A spark may not necessarily be due to a defective porcelain and a cracked porcelain may be so full of moisture as not to spark.

Conclusion D If the series resistance is entirely eliminated and the charging current of the insulator is taken through the telephone with a series gap gradually increased, a result will be obtained quite contrary to the ones just described. When the resistance is not in series and with the tiniest spark playing, a very high pitch is obtained which is something more than a noise and may be described as a rather disagreeable musical note. For small gaps the sounds are somewhat similar to those with resistance in series. As the gap opens the pitch decreases and the noise becomes very scratchy beyond 0.02 in. Beyond this gap also, the noise begins to decrease in intensity until the maximum spark gap, about 0.35 in. is reached when the sound has very greatly decreased although it is still audible. It has very little resemblance to the sound given by the same spark length when the resistance is in series. It should be noted that the sound decreases rather than increases with the gap length after the first 0.01in. or 0.02 in. is passed. The high pitched noises at small gap lengths are due, partially at least, to many successive sparks jumping the gap for every cycle of the generator wave. Larger gaps require more voltage built up before the spark takes place and therefore there are a less number per cycle.

If this method then is applied to an insulator on a metal tower, quite different intensities of sound will be obtained from those on a wooden pole line.

It seems desirable to endeavor to point out the cause of the difference in the sound in the telephone receiver when the series resistance is used and when not. With a high resistance in series the condenser discharge from the insulator capacitance is so thoroughly damped that it passes through the telephone as a single impulse and we get the effect on the iron disk of a single blow on the bottom of a dish-pan. When there is no series resistance the discharge of this condenser is damped comparatively little and as a result the iron disk of the telephone will receive a blow first in one direction and then in the other direction as the logarithmic wave dies out. This frequency is so high that the inertia of the disk will not allow it to move in synchronism with the oscillation. Therefore each half-cycle of the oscillation counteracts the previous one, leaving the disk almost stationary. As a result there is a very little sound given out.

Conclusion E. It is found that when the resistance in parallel with the telephone has a value five times the resistance of the telephone there is an appreciable diminution in the sound. As the shunting resistance increases the sound gradually increases and above 20 to 50 times the resistance of the telephone, the sound in the telephone has approximately its full value.

TESTS WITH DEFECTIVE PIN-TYPE INSULATORS

These tests were made on seven defective insulators furnished the writer by Mr. P. M. Downing from the Pacific Gas & Electric Company's lines last fall. To avoid prejudicial information the tests with the telephone were carried out without any regard to the defects of the insulators and subsequently the insulators were tested up with the megger on each separate skirt and the defective ones listed. The data were then rearranged for the convenience of the reader, placing the insulators in the order of their defectiveness, the least defective being placed first.

These insulators were used on 60-kv. circuit and their Y voltage would therefore be about 35 kv. The record given here is for an application of 43 kv. which is 23 per cent above the Y voltage. The reasons for this choice were several-fold. In the first place the laboratory was noisier than the usual location of a transmission pole. Second, it was desired to make the laboratory test a little more severe than the usual conditions of the line to make up for high-voltage surges which would naturally occur on the line, and third, an endeavor to make the test voltage a little more severe than could be found in practise with the idea of determining the best results which might be obtained in actual service. No doubt with a more sensitive telephone receiver more noise could have been obtained but it is doubtful if the greater intensity of noise in the telephone receiver would have given any distinguishing effect. This conclusion is drawn from the fact that perfect insulators of the suspension type gave more noise by internal brush discharge than the defective insulators of the pin type.

The first test consisted in connecting up the pin to one terminal of the insulator and allowing the other connection to hang in the air parallel to the insulator about 8 in. away. A very considerable corona could be heard directly on this wire but no appreciable sounds could be detected in the telephone receiver. This shows that any noise obtained does not come from the distant points of the loads but must come from those more directly in contact with the porcelain.

Tests on Insulator No. 1. This insulator originally measured less than 10 megohms on skirts 3 and 4, counting the skirt next to the line as No. 1. However, it had dried out at the time the telephone test was made and all four skirts measured infinity. The voltage was raised on this insulator up to 50 kv. without giving any distinguishing sound in the telephone which would indicate that it was defective.

Tests on Insulator No. 2. The second skirt of this insulator measured 2000 megohms and the other three skirts infinity. This insulator also up to 50 kv. applied gave no distinguishing sound to indicate its defectiveness.

Tests on Insulator No. 3. This insulator originally meggered less than 10 megohms on skirts 2 and 3 but by drying out it measured 2000 megohms on skirt 2 and infinity on skirt 3, and subsequent to the last test, skirt 4 developed defectiveness and had a resistance of 10 megohms. As it stands at the present time then, skirt 4 measured 10 megohms and skirt 2, 2000 megohms. At 43 kv., 23 per cent above Y voltage, there was no audible sound to indicate defectiveness. However, at 50 kv. a distinct brush discharge could be heard. This sound of the brush discharge is sufficiently different from the spark of the gap in series to be distinguished but not described. The defect in this insulator could not be told by our telephone tests.

Tests on Insulator No. 4. This insulator was slightly worse than the previous one in that skirt 2 measured less than 10 megohms—how much less is not known since the megger needle went to its zero value. Skirt 4 gave 2000 megohms. With 68 megohms in series to represent the resistance of a transmission pole no distinguishing sound of fault could be heard in the telephone either at 43 kv. or at 50 kv. When the series resistance was cut out there was a sound such as a slight, distributed brush discharge in an insulator would give. At 50 kv. this sound of brush discharge was intensified but there were no indications of sparks taking place internally in the insulator. It should be noted that series resistance decreased the sound of the telephone and is just the contrary to the effect obtained with a long series gap where the spark could take place in concentrated form. Attention is called to this fact to show the various sounds that can be given out under the various conditions. The operator must learn these sounds that correspond to the different conditions by actual use. This experience has a bearing on how near to the insulator the lineman must be in order to obtain the desired degree of intensity. Again his personal judgment must be depended upon.

Tests on Insulator No. 5. This insulator originally meggered less than 10 megohms on both the 3rd and 4th skirts. However, at the time of test the third skirt had risen to 30 megohms With a series resistance of 68 megohms and the potential at 43 kv. there was no distinguishing sound of defectiveness.

With the series resistance cut out there was quite a distinct brush discharge audible at 43 kv. At 35 kv. it was proportionately less, although it is very probable that the noise of the brush discharge might be sufficient to throw this insulator under suspicion.

At 50 kv. applied an internal spark suddenly took place. The difference in the sound was unmistakable.

Tests on Insulator No. 6. This insulator was slightly more deteriorated than No. 5 in that both skirts 3 and 4 measure less than 10 megohms. The needle of the thousand-volt megger went against its zero spot.

The same sound of brush discharge could be heard on this insulator as on the previous one. At 50 kv., however, only the brush discharge was intensified without giving any sound of internal spark.

Tests on Insulator No. 7. This insulator was the worst of all, having the 2nd, 3rd, and 4th skirts all meggering too low to read on the thousand-volt megger. On this insulator very little sound of brush discharge could be heard at 43 kv. when 68 megohms of series resistance was used. Without the series resistance, however, distinct sounds of brush discharge could be heard at voltages as low as 15 kv. At 43 kv. and no series resistance, there was not only a loud noise of the brush discharge but also a superposed sound of higher pitch. There can be no doubt that by this method any operator with the slightest experience could detect this insulator as faulty.

General Conclusions. These data lead one to the following tentative conclusions regarding this method of test:

1st. The method apparently cannot give good results for porous insulators with either air or water in the pores although such porcelain is defective.

2nd. Insulators with three petticoats out of four defective showed up with great intensity. Insulators with two skirts out of four defective may apparently be distinguished in many cases provided series resistance is eliminated by making the telephone connection near the insulator pin.

3rd. Considerable difficulty will be encountered using the method on a metal tower with the pins grounded. A low resistance telephone will then be desirable and possibly a ground connection separate from the tower legs.

4th. Certain conditions on the line will make the method more favorable there than in the laboratory tests, such as quiet surroundings and more high-voltage surges. On the other hand, certain disadvantages may be encountered in the presence of the higher harmonics of the generator, especially the 11th, 13th, 17th and 19th harmonics which correspond to 12 teeth per pair of poles and 18 teeth per pair of poles. These harmonics will be more or less magnified by the capacitance of the line, depending upon how much the circuit is loaded. Such harmonics will give a different timbre to the sound in the telephone.

5th. The laboratory tests would indicate that roughness in the surface of the Portland cement, such as might be caused by the presence of an air bubble on the surface of the porcelain at the time the cement was set, might cause local brush discharge indistinguishable from the noise produced by a defective porcelain. Such a local spark can be easily reproduced experimentally by twisting a wire around the metal pin of a suspension insulator and extending it out a fraction of an inch, leaving the point not quite in contact with the porcelain.

6th. With all that has been said regarding the possible inaccuracies of this method, it still remains as a very cheap and simple method of detecting pin-type insulators which are in an advanced stage of deterioration.

Presented at the Pacific Coast Convention of
the American Institute of Electrical Engineers,
Seattle, Wash., September 6, 1916

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THE HIGH-VOLTAGE POTENTIOMETER

BY HARRIS J. RYAN

Abstract of Paper

The author describes a high-voltage potentiometer which may be made at reasonable expense consisting of a water resistance potential distributor and a sparking probe potential difference detector. The water resistance consists of a column of water moving slowly through an ample length of garden hose, and tapping in points through which to connect the probe are provided by breaking the hose at regular intervals and connecting it with any of the plain metal connectors found on the market as "hose menders." The results of an integrity trial are charted in Fig. 2. The device is intended for investigations in which the results are not required to be known within 2 or 3 per cent of their actual value.

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THE potentimoter method for the determination of altering potentials or for the measurement of alternating-voltage duties requires: 1. A *distributor* of alternating potential, identical in phase and wave form with the alternating potential to be determined. 2. A satisfactory potential difference *detector* to determine when the known potential from the distributor matches the unknown potential to be measured. For a high-voltage potentiometer at reasonable expense the following types are feasible:

A source of synchronous variable voltage that matches the voltage to be measured in phase and wave form; requires a phase-shifting transformer and an induction regulator or a suitable multiple-tap transformer.

A condenser connected to the high-voltage source having a variable potential feature as follows: A fluid dielectric and a potential tapping plate electrode that may be moved to any position between the main electrodes of the condenser, or a series of electrode potential plates mounted in the dielectric between the main electrodes at uniform intervals.

A chain of equal water resistances connected across the same high-voltage source as the test specimen from which any required potential may be tapped.

There are two types of detector available:

The sparking probe.

The Bennet small current oscillograph.*

In the sparking probe detector advantage is taken of the fact that a spark occurs at a pointed electrode when used to connect two condensers charged to different potentials. This is true even when the capacitances and differences of potentials are small. In the Bennet detector an oscillograph with suitable auxiliary equipment is used to observe the charging current taken by the insulator system under observation, and to note when the potential applied to a conductor is such that it may be brought in contact with a metal part of the insulator system without disturbing the normal value of such charging current.

The author has had experience in the development and use of these several potential distributors and the sparking probe detector. He has had no experience with the Bennet detector, though he is convinced, from his own experience, that such detector will yield reliable results. Of the several expedients specified it has been found that the water resistance distributor and the probe detector constitute a convenient and reliable high-voltage potentiometer that may be constructed of common materials with ordinarily skilled labor at small cost. A column of water moving slowly through an ample length of garden hose constitutes the resistance. The length of hose required for a given over-all voltage may vary considerably. The author has used *one foot* (30.4 cm.) of hose *per one thousand* maximum range effective *volts*. Tapping-in points from which to connect the cable leading to the probe are provided by breaking the hose at regular intervals and connecting it with any of the plain metal connectors found on the market as "hose menders". The illustration in Fig. 1 was taken from a photograph of one of these water column potential distributors. The hose is of the common *three-quarter-inch* (1.9 cm.) variety, 75 ft. (22.8 m.) long, in 50 sections of 18 in. (45.6 cm.) each. It is formed into a cylindrical helix of twelve and one half turns on a diameter so as to use four sections per turn and so as to make corresponding metal connectors line up in four columns on the surface of the helix-cylinder. The turns are spaced, insulated and held together by strain insulators and light galvanized steel strands

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*Distributing Potential over a String of Insulators. By J. L. Brenneman and Harold M. Crothers. *Electrical World*, Vol. 64, Dec. 5, 1914. p. 1095.

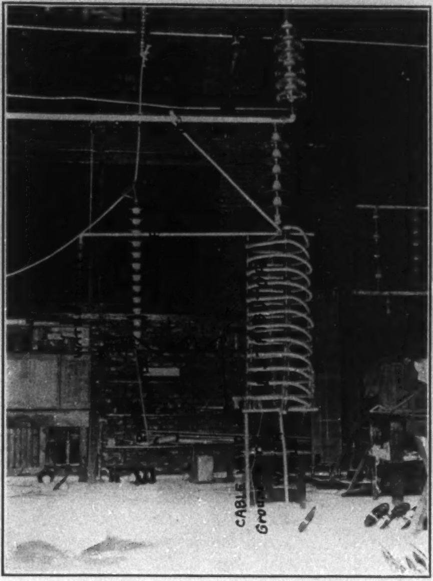
CABLE
Ground

FIG. 1—HIGH VOLTAGE POTENTIOMETER [RYAN]

located at the metal connectors. The hose starts at the bottom from one branch of a supporting cross formed of *three-quarter*-in. (1.9 cm.) galvanized iron pipe and a five-way fence-pipe fitting. It ends at the top in a branch of a duplicate pipe structure. The bottom end is attached to the water supply and grounded if this water connection is made through rubber or other non-conducting hose. The branch of the top cross is connected to one of the high-voltage source terminals and extended horizontally to a convenient distance, five ft. (1.5 m.), and terminated downward in a common sprinkler nozzle. The openings in the nozzle are large and numerous enough to permit ample exit of water without pressure. The water then falls away in drops, thus breaking the circuit that would otherwise be formed in parallel with the distributor circuit.

One of the four columns formed by the strain insulators is selected for mounting the tapping-in terminals of the conductors that lead through the interior of the helix to their corresponding metal hose connectors. These tap conductors are made of No. 10, B. & S. gage galvanized steel wire. To make probe connecting terminals at the outer ends of these tapping wires, such ends are formed into nearly complete rings finished with eyes and clamped with small bolts in proper order around the strain insulators. In an over-all sense this construction is strategic against corona formation.

Ordinarily 75 kilovolts will set up 50 milliamperes through this distributor. The amount of the current naturally depends upon the temperature of and the impurities in the water. Obviously variation in the value of the current through the distributor does not affect the integrity of the potentiometer results. It is only necessary in connection herewith that the current shall always be large compared with the charging current that passes from the probe cable to surrounding objects. The length of the cable used with this distributor is *ten* ft. (three m.) Its capacitance to earth does not exceed 0.000025 microfarads and the charging current liberated from it at 75 kilovolts to earth is, therefore, not more than *seven-tenths* of a milliampere.

The development and study of these various forms of high-voltage potentiometer was begun in March, 1912. Many integrity trials of them have been made. Some of the results thus obtained have been published.* The water resistance

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*High-Voltage Potentiometers *Jour. Electricity, Power, and Gas*, Vol. 34, April 10, 1915.

distributor was developed during the present year and after the author was told by Mr. Faccioli that a resistance distributor had been found to give excellent results. Experience with the transformer and condenser types of distributor showed that the water resistance distributor must yield reliable results, consequently only one integrity trial of it has been made, and that with no particular care. In this trial the potentials of a light chain were determined when suspended in the electric field formed between two parallel lengths of pipe by 140 kilovolts. The chain was mounted at various distances from one of the conductors and its corresponding potentials were determined by the potentiometer and calculated from the known dimensions. The results are charted in Fig. 2. No great accuracy is claimed for the outfit. It is intended only for those studies in which the results are not required to be known within two or three per cent of their actual values.*

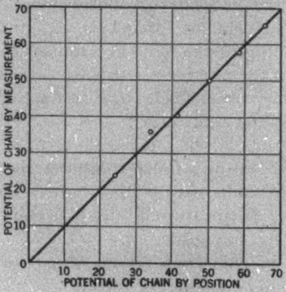

FIG. 2.

The potentiometer may be used to determine the potential of any outline or surface of an insulation system whereat or where-on a metal wire or sheet may be mounted and to which the potential probe can be applied. Such wire or sheet is called the insulator *potential electrode.* In general the capacitance of the insulator potential electrode is relatively small. The effect of the presence of the probe will, therefore, be such as to alter the potential of the electrode somewhat. The only result thereof is to widen the zone of potential through which the detector indicates an equally good balance. This effect occurs alike above and below the true potential of the insulator electrode and is eliminated by reading at the middle of the potential balance zone. The true balance must often fall between the potential taps as actually provided in the distributor. This is an additional cause that generally prevents a tap being found at which absolutely no probing spark is discernable in full darkness. For example in securing the results charted in Fig. 2 when the center of the chain was located seven in. (2.1 m.) from the surface of one of the high-voltage conductors a faint but definite spark occurred between the probe point and chain at the 22 per cent tap and again at the 25 per cent tap; 23.5 per cent of the line voltage was, therefore, given as the reading for the potential of the chain in this position. When the probe point was applied to the chain carrying potential tapped at 23 and 24 per cent of the line voltage, barely discernable sparks passed; they did not differ in recognizable degree showing that the true balance occurred midway between them.

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*It should be noted that the results of the integrity trial charted in Fig. 2 embrace two classes of errors, only one of which is chargeable to the potentiometer, while structural deformities and defects in chain location measurements are responsible for the other.

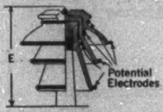

FIG. 3.

It is not thought necessary to discuss matters of this sort further. It is believed that anyone whose general training and experience have prepared them to take up work of the present character will have no difficulty in learning quickly from their own perceptions and efforts the correct procedure for this sort of potentiometer. Obviously two persons must work together to apply it. One handles the probe and the other handles the probe cable from tap to tap in the distributor until a potential balance is found. The probe and tap ends of the probe cable are each handled at the end of a suitable stick of clear quality wood, such as redwood, white pine or poplar, impregnated with paraffin as a precaution against the absorption of water. In work upon such insulation systems as a suspension type insulator the person or the operator should be as distant as possible and permit of the proper handling of the probe in order that the electric field about the insulator and therefore the voltage duties of its parts will not be disturbed. It is thought unnecessary to point out the many expedients that may be employed in locating and mounting insulator potential electrodes so as to explore the intensity of the electric fields in the air, oil or within the solid dielectrics of any system of insulation. These will promptly suggest themselves to anyone likely to have work of this sort on his hands to do.

In Fig. 3 the cross section of a pin-type insulator is given showing the location of wire hoops to constitute insulator potential electrodes for the purpose of determining the voltage duty of the air about the insulator, over its surfaces and through its solid sections. It is obvious that these wire hoops must be located in equipotential surfaces. Their presence does not disturb the electric field nor the voltage duties of the insulator parts and of the surrounding air.

Presented at the Pacific Coast Convention of the American Institute of Electrical Engineers, Seattle, Wash., September 6, 1916.

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AN ARTIFICIAL TRANSMISSION LINE WITH ADJUSTABLE LINE CONSTANTS

BY C. EDWARD MAGNUSSON AND S. R. BURBANK

ABSTRACT OF PAPER

A description is given of an artificial transmission line which can be readily adjusted to represent 200 miles (321.86 km.) of commercial transmission lines of any spacing up to a maximum of 120 in. (3 m.) and any size wire up to 4/0 copper. It can also be made to correspond to aerial or cable telephone lines and to power cables. The use of this type of line in laboratory courses on transmission line phenomena is illustrated by a number of typical experiments. It is shown that quantitative data, sufficiently accurate for instructional purposes, may be obtained by using portable voltmeters and ammeters and by the oscillograph.

THAT artificial transmission lines can be used to advantage in investigations on transmission line phenomena is well known. It has been proved by extended research* that actual transmission line phenomena can be accurately reproduced in laboratory structures and that the theoretical equations correctly express the quantitative relations between the line constants, voltages, currents, time and space phase angles and other factors that enter in the general transmission line problem. Artificial transmission lines have, however, been used only to a very limited extent either as laboratory apparatus for experimental work by students in power transmission courses, or by engineers when investigating industrial transmission systems. Very few engineering colleges have any facilities for laboratory work on transmission lines. The instruction is given by lectures, text-book recitations and class-room problems, without the aid of quantitative laboratory experiments. As a consequence comparatively few students gain a clear insight into transmission line phenomena, and although they may be able to develop the standard equations they fail to comprehend the physical phenomena involved or to understand what actually takes place in the transmission system. That quantitative laboratory experiments would be as desirable in the study of transmission lines as the customary experimental work in courses on alternators, motors or telephones, is admitted. The difference in practise has been due chiefly to a lack of suitable apparatus for giving laboratory instruction on transmission lines.

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*See Bibliography on page 1257.

The purpose of this paper is to describe the design and construction of an artificial transmission line adapted to the requirements of laboratory apparatus for undergraduate instructional experiments as well as for research, and to report a few typical experiments. The line has been in successful operation for the past three years in the Electrical Engineering Laboratories of the University of Washington. It consists of twenty units connected in series as shown in Fig. 1. Each unit, Fig. 2, is complete in itself and represents approximately ten miles of a power transmission line. The line can readily be adjusted, within wide limits, to any spacing or size of wire, or converted into a standard telephone line. The wiring diagram for the units is shown in Fig. 3 and for the complete line of twenty units in Fig. 4. The apparatus represents one line to neutral and can therefor be used in experiments on either single-phase or polyphase systems. The diagram shows that the line is of the " lumpy " type, similar to the artificial line at Harvard University,* with the condensers connected at the middle point of the inductance in each unit. While lines with uniformly distributed† inductance, condensance and resistance comply strictly with actual transmission line conditions the first cost and maintenance are much greater than for the "lumpy" type. Moreover the latter type can be made adjustable so as to represent

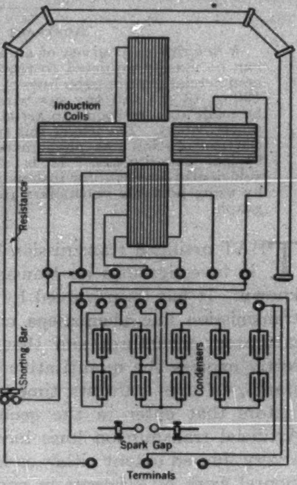

FIG. 3—WIRING DIAGRAM OF EACH UNIT

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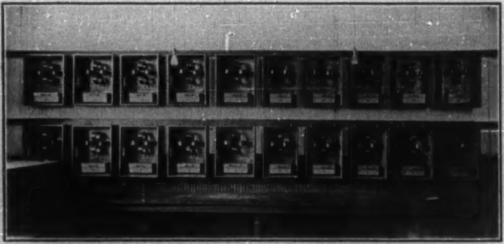
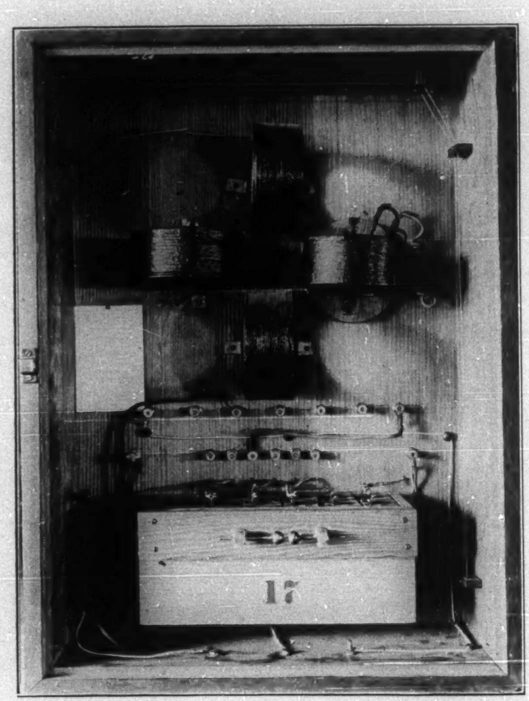
*See bibliography Numbers 5, 6, 7, and 8.

†See Bibliography Numbers 2 and 3.



[MAGNUSSON AND BURBANK]

FIG. 1—COMPLETE LINE OF TWENTY UNITS



[MAGNUSSON AND BURBANK]

FIG. 2—ASSEMBLED UNIT

lines of almost any size of wire and for different spacings. The spark gap on each unit can be adjusted so as to provide protection to the condensers against excessive voltages that may develop under resonance conditions. The ten-mile unit was selected as a sufficiently close approximation to the uniformly distributed line constants of industrial transmission lines for frequencies up to 800 cycles per second.

Both for instructional and research purposes it is desirable to have an apparatus that can be adjusted so as to represent lines differing, not merely in length, but also in size and spacing of the conductors. This line is so designed that it can readily be adjusted so as to correspond to a line of any spacing up to 120 in. (305 cm.) and for any size of wire up to No. 4/0 hard-drawn copper. By the insertion of a 50-ohm non-inductive resistance between the units it is converted into a telephone line of practically standard specifications.

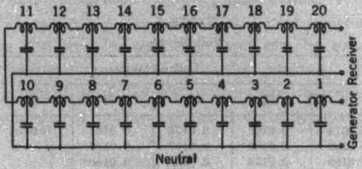


FIG. 4—WIRING DIAGRAM OF COMPLETE LINE

To comply with the above requirements the line constants must be adjustable within the following limits:

Resistance, minimum value = 2.59 ohms.
Inductance, maximum value = 0.021 henry;
Condensance,............ = from 0.1 to 1.0 microfarad

Resistance. The resistance of the inductance coils must not exceed minimum resistance in the unit, each of the four coils must be equal to or less than 2.59 ÷ 4 = 0.65 ohm. Selecting No. 14 A. W. G., d. c. c., copper, the length of wire in each coil must not exceed 257 ft. (78.3 m.). The coils as constructed* have 250 ft. each, thus allowing for the resistance of the connecting wires and for a slight adjustment when the line represents No. 4/0 copper wire. For lines with smaller sized conductors the additional resistance is obtained by moving the short-circuiting clamp on the loop of "Advance" resistance wire. Figs. 2 and 3.

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*Bibliography No. 11.

Inductance. The inductance is obtained from four short air-core solenoids arranged in a square. For a given length of wire the inductance depends on the dimensions of the coil. The required dimensions were obtained by means of Brooks Formula†. The final dimensions of the coils as constructed are:

Mean radius	2.20 inches	(5.59 cm.)
Length of coil	2.15 "	(5.47 cm.)
Thickness of winding	0.60 "	(1.52 cm.)
Length of wire	250. feet	(76.3 m.)
Number of turns (eight layers of twenty-seven turns each)	216.	

The mutual inductance is very nearly 8 per cent of the self-inductance for each unit. With the coils in position the measured value corresponds to the amount required.

The inductance in each unit can be varied by turning the right hand coil and by using the taps on the lower coil. Any inductance up to the maximum value can be obtained by making the proper adjustments. All the units have been calibrated showing the inductance for five positions of the movable coil and for four taps on the lower coil as illustrated in Table 1.

TABLE I.

Unit No. 15.

Position of movable coil	Coils in Series					
	4	3¾	3⅝	3½	3	2
0°	0.0214	0.0193	0.0176	0.0161	0.0154	0.0098
45°	0.0209	0.0186	0.0167	0.0156	......	......
90°	0.0199	0.0178	0.0160	0.0149	......	......
135°	0.0188	0.0171	0.0158	0.0145	......	......
180°	0.0185	0.0168	0.0152	0.0142	......	......

The average maximum inductance for the whole line is 0.0213 henry for each unit. The measured inductance for the several units varies from 0.021 to 0.022 except for unit No. 2 which is 0.0197 henry.

Condensance. The line condensance is obtained from 200 standard telephone condensers, type No. 21-AA, guaranteed to stand 1000 volts. Each unit has ten condensers connected in series with taps brought out at the terminals of the 5th, 6th, 7th, 8th, 9th, and 10th condenser. Each unit has been calibrated and the results tabulated as illustrated by Table 2.

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†University of Illinois, Bulletin No. 53.

A spark-gap was connected across the condensers as a protection against voltages in excess of the rated value of 1000 volts per condenser. Under resonance conditions this protection is necessary.

Cost. The cost per unit was approximately $24.00, or a total of $480.00 for the complete line of twenty units.

Instruments. For accurate measurements an a-c. potentiometer is necessary and an instrument like the Drysdale-Tinsley alternating and continuous current potentiometer gives excellent results. Unfortunately the potentiometer is expensive and requires more skill in the operator than can be expected from ordinary students in power transmission courses. Quantitative values, sufficiently accurate for instructional purposes, may be obtained by means of ordinary portable voltmeters and ammeters, for numerous experiments, as may be seen by comparing the calculated and the observed values in several of the experiments described in this paper. The instruments used were Standard voltmeters, ammeters, speed indicators, and a three-element oscillograph.

TABLE II.
Unit No. 15.

	Number of condensers in series.					
	5	6	7	8	9	10
Microfarads	0.182	0.151	0.131	0.114	0.102	0.092

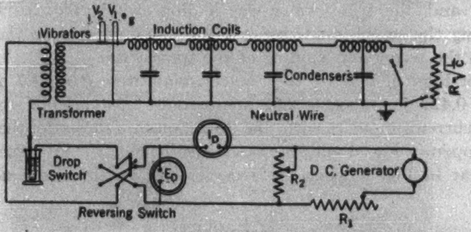


FIG. 5—WIRING DIAGRAM FOR IMPULSE OSCILLOGRAMS IN FIGS. 6, 7, 8, 9, 10, 11

Great care must be exercised in keeping the frequency constant throughout each test. Slight changes in frequency will cause considerable changes in the voltmeter and ammeter readings.

Typical Experiments. The experimental data have been selected from student's laboratory reports, and credit is due Mr. R. Rader for Figs. 6, 7 and 8; Messrs. G. S. Palmer and D. K. Chaudhuri for Figs. 13 to 18 and 20 to 27; and Messrs. S. R. Burbank and F. T. Yamada for Figs. 9 to 11 and 28 to 37.

The circuit connections are shown in Figs. 5, 12 and 19 for each experiment. The oscillograms and the drawn curves are in a large measure self-explanatory. In all cases the size of wire was equivalent to No. 4/0 hard-drawn copper. The spacing was either 96 in. or 120 in. (2.4 or 3 m.) as noted below each figure. Experiments with other spacings and for other sizes of wire gave similar results.

The experiments selected may be grouped into three divisions:

1. Sudden impulses impressed on the line.
2. Voltage and current readings along the line. Constant voltage at the generator end and constant frequency.
3. Resonance.

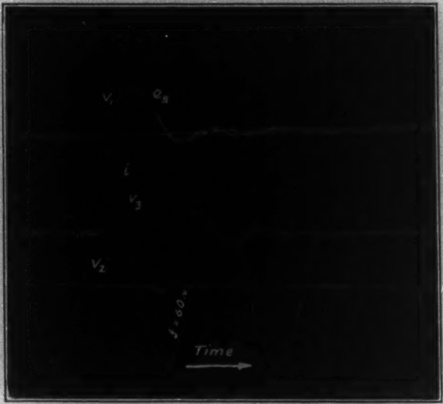
GROUP 1

A direct-current generator was connected to the primary of a transformer and the line to the secondary. Between the generator and the transformer was a drop switch, Fig. 5. Upon closing the switch a sudden impulse was impressed on the line from the secondary winding of the transformer.

For Figs. 6, 7 and 8 the line constants were $R = 51.7$ ohms, $L = 0.427$ henry, $C = 2.92$ microfarads. The original voltage and current impulses with the reflections are shown for receiver end open in Fig. 6 and short-circuited in Fig. 7. No reflections appear in Fig. 8 when the receiver has a resistance equal to

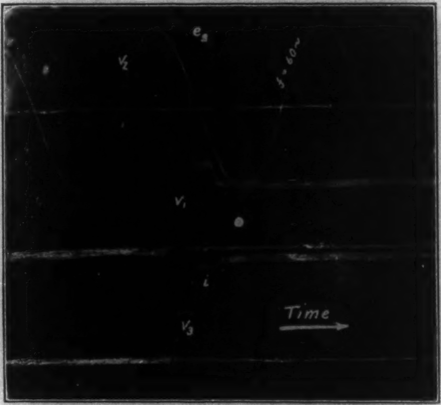
$$\sqrt{\frac{L}{C}} \text{ ohms.}$$

Calculating the length of the line from the line constants it should be equivalent to 208 miles (334.7 km.). Measuring the time taken for the impulse to be reflected from the receiver end as in Fig. 7, and assuming a velocity of 3×10^{10} cm. per second, the equivalent length of line was 214 miles (334.4 km.). A number of trials gave a similar discrepancy of approximately 3 per cent. In the fall of 1916 the condensers, a cheap grade, were replaced by Type 21-AA condensers. Measurements on



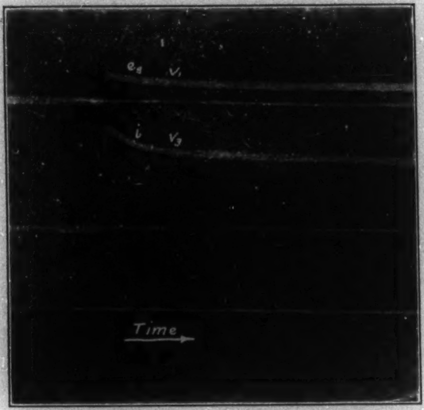
[MAGNUSSON AND BURBANK]

FIG. 6—RECEIVER END OPEN
Spacing 120 in. — E_D = 98 v. — I_D = 6.00 amp.



[MAGNUSSON AND BURBANK]

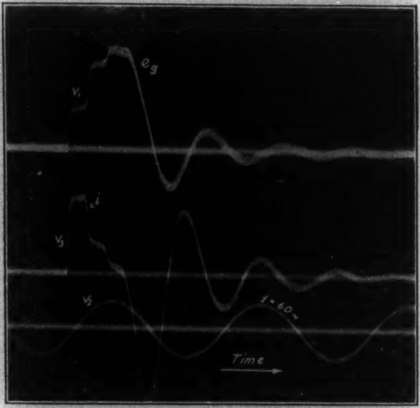
FIG. 7—RECEIVER END SHORT CIRCUITED
Spacing 120 in. — E_D = 100 v. — I_D = 2.5 amp.



[MAGNUSSON AND BURBANK]

Fig. 8—Receiver End Closed Through $\sqrt{\frac{L}{C}}$ Ohms

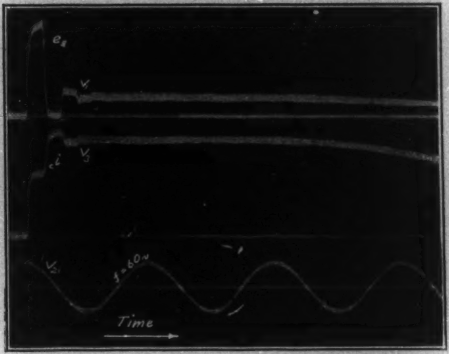
Spacing = 120 in. – E_D = 104 v. – I_D = 2.3 amp.



[MAGNUSSON AND BURBANK]

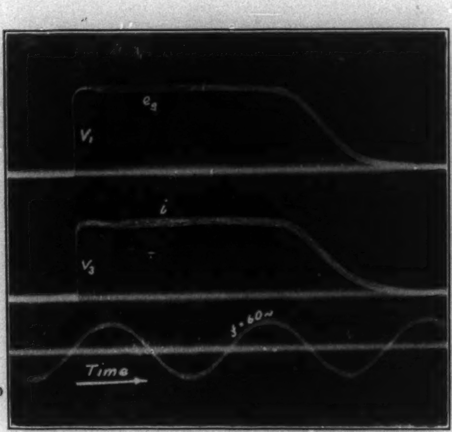
Fig. 9—Receiver End Open

Spacing = 96 in. – E_D = 110 v.– I_D = 19.8 amp.



[MAGNUSSON AND BURBANK]

FIG. 10—RECEIVER END SHORT CIRCUITED
Spacing = 96 in. – E_D = 101 v. – I_D = 20.0 amp.



[MAGNUSSON AND BURBANK]

FIG. 11—RECEIVER END CLOSED THROUGH $\sqrt{\frac{L}{C}}$ OHMS
Spacing = 96 in. – E_D = 110 v. – I_D = 19.7 amp.

oscillograms taken after the new type of condensers were on the line, as in Figs. 9 and 10, checked more closely with the length calculated from the line constants. Thus for Figs. 9, 10 and 11 the line was adjusted for a spacing of 96 in. (2.4 m.) The line constants were R = 52.9 ohms; L = 0.412 henry; C = 3.03 microfarads. From the line constants the equivalent length of line was 208.5 miles (335.5 km.) From measurements on the oscillogram in Fig. 9 the equivalent length was 206.5 miles (332.3 km.) and from the oscillogram in Fig. 10, 208 miles (334.7 km.) A slight leakage in the first set of condensers probably caused the retardation of the electromagnetic wave. After three reflections in the open line, (Figs. 6 and 9) the transformer and the line oscillate together causing an oscillatory transient of lower frequency.

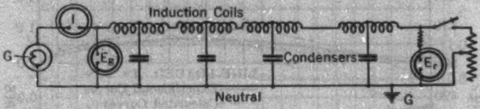


Fig. 12—Wiring Diagram for Line Characteristics, Figs. 13, 14, 15, 16, 17, 18—and Resonance Curves Figs. 28 and 33

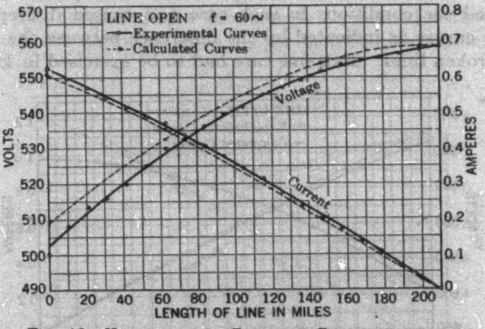


Fig. 13—Voltage and Current Characteristics

Group 2

The change in the magnitude of the voltage and current along the line is shown in Figs. 13 to 18, inclusive, for the line open and for frequencies of 60, 100 and 120 cycles, respectively, in Figs. 13, 15 and 17, and similarly for the line loaded so as to have generator and receiver voltages each equal to 500 volts, in Figs. 14, 16 and 18.

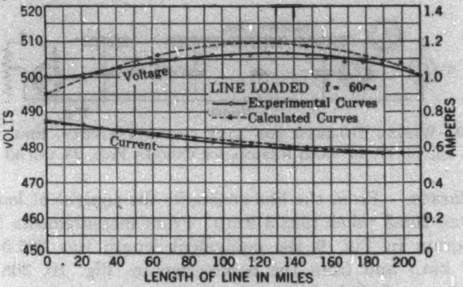


Fig. 14—Voltage and Current Characteristics

Necessarily the shunting of the voltmeter across the line changed the conditions in each case and caused discrepancies in the curves as indicated by the difference between the drawn and broken lines. Extreme care had to be exercised in keeping

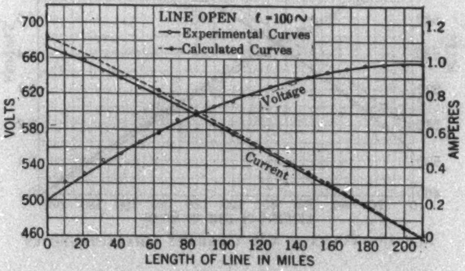


Fig. 15—Voltage and Current Characteristics

the frequency constant for each set of readings. A slight change in frequency will cause a considerable change in the receiver voltage with the line open. This is readily seen by comparing the receiver voltages for 60, 100 and 120 cycles in Figs. 13, 15 and 17.

GROUP 3

In obtaining the data on resonance, two single-phase alternators were used. Alternator *A* gave a voltage wave which appeared to be simple harmonic but on analysis was found to have a small third harmonic, about one per cent, of the fundamental. The shape of the voltage wave of alternator *B* is shown in Fig. 32, consisting of a fundamental combined with a 28.2 per cent third harmonic and a 5.4 per cent fifth harmonic. The frequency of alternator *A* was normally 137 cycles and for *B*, 60 cycles.

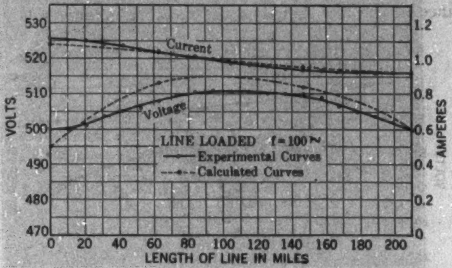


FIG. 16—VOLTAGE AND CURRENT CHARACTERISTICS

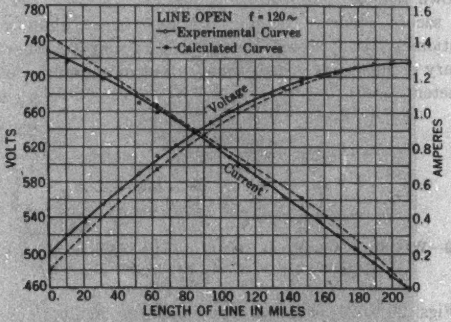


FIG. 17—VOLTAGE AND CURRENT CHARACTERISTICS

At first it was assumed that alternator *A* gave a simple sine wave. The first indications that the assumption was not true were difficulties in securing consistent readings at all frequencies, particularly between 70 and 75 cycles. With the generator voltage of 1000 volts and the frequency about 72 cycles, the condensers in unit No. 20, at the receiver end, were punctured. Upon investigation it was found that the third harmonic caused resonance in the line and that the receiver voltage was greatly in excess of what would be produced by the fundamental. To prevent a similar accident spark-gaps were placed in each unit as shown in Figs. 2 and 3.

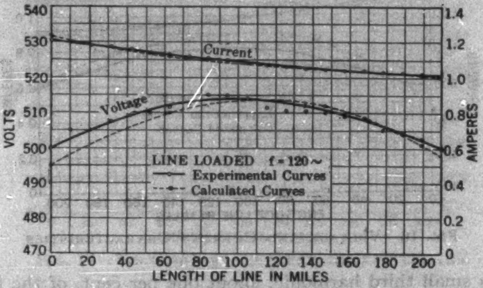


FIG. 18—VOLTAGE AND CURRENT CHARACTERISTICS

To secure accurate readings on resonance values, an a-c. potentiometer is necessary, but the effect may be observed on ordinary oscillograms and to some extent measured by portable voltmeters.

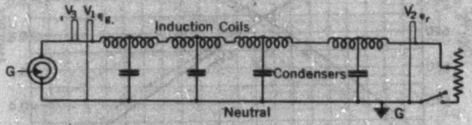
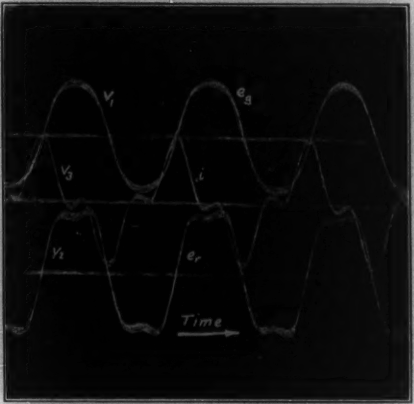


FIG. 19—WIRING DIAGRAM FOR OSCILLOGRAMS IN FIGS. 21, 22, 23, 24, 25, 26, 27, 29, 30, 31, 34, 35, 36, 37

In Figs. 20 to 24, inclusive, are shown the oscillograms of the generator and receiver voltages and the charging current for 60, 66, 72, 100 and 120 cycles using alternator *A*. The generator voltage is nearly a sine wave in all cases. The receiver voltage and the charging current show a third harmonic in Fig. 20; an increased distortion in Fig. 21 and a maximum third harmonic



[MAGNUSSON AND BURBANK]

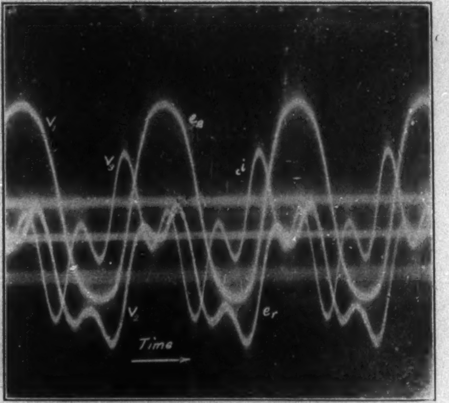
FIG. 20—RECEIVER END OPEN

Spacing = 120 in. – f = 60 ~ – L = 0.427 h. — C = 2.96 mf. – E_g = 500 v. – E_r = 558 v – I = 0.63 amp.

[MAGNUSSON AND BURBANK]

FIG. 21—RECEIVER END OPEN

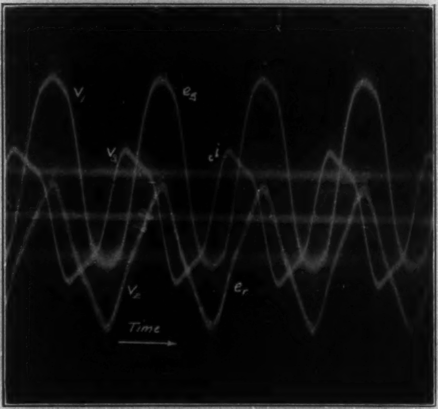
Spacing = 120 in. – f = 66 ~ – L = 0.427h. – C = 2.96 mf. – E_g = 500 v.



[MAGNUSSON AND BURBANK]

FIG. 22—RECEIVER END OPEN

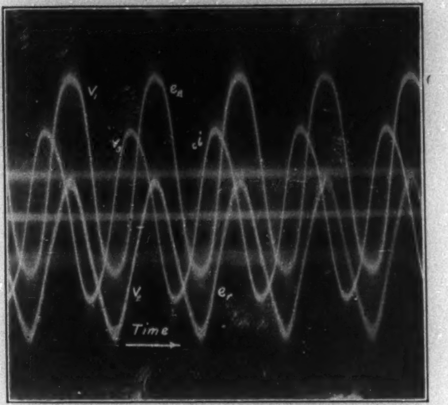
Spacing = 120 in. – f = 72 ~ – L = 0.427h. – C = 2.96 mf. – E_g = 500 v.



[MAGNUSSON AND BURBANK]

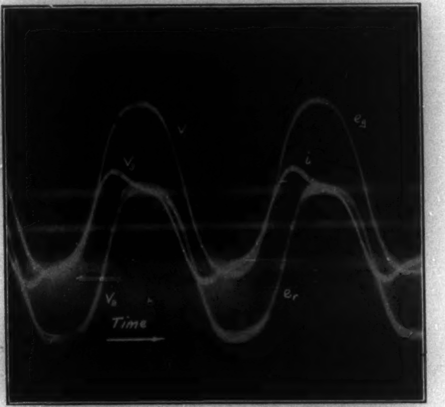
FIG. 23—RECEIVER END OPEN

Spacing 120 in. – f = 100 ~ – L = 0.427 h. – C = 2.96 mf. – E_g = 500 v. – E_r = 655 v. – I = 1.06 amp.



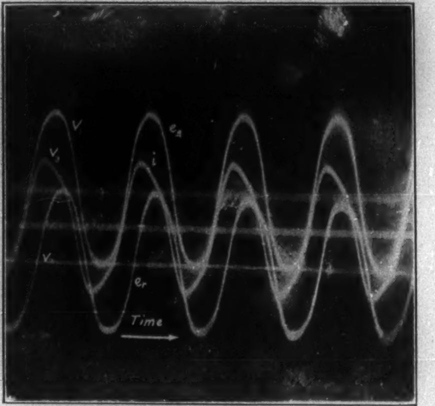
[MAGNUSSON AND BURBANK]

FIG. 24—RECEIVER END OPEN
Spacing 120 in. – $f = 120 \sim$ – $C = 2.96$ mf. – $L = 0.427$ h. – $E_g = 500$ v. – $E_r = 716$ v. – $I = 1.34$ amp.



[MAGNUSSON AND BURBANK]

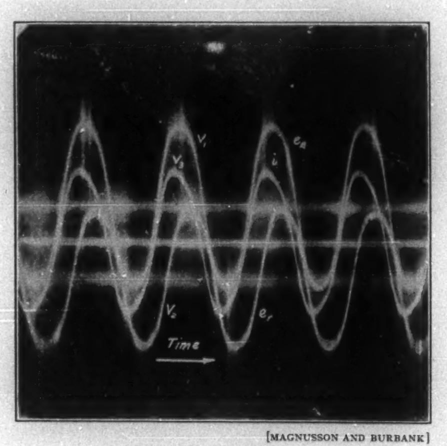
FIG. 25—RECEIVER END LOADED
I_r – 0.56 amp. – Spacing 120 in. – $f = 60 \sim$ – $C = 2.96$ mf. – $L = 0.427$ h. – E_g – 500 v. – $E_r = 500$ v. — $I = 0.75$ amp.



[MAGNUSSON AND BURBANK]

FIG. 26—RECEIVER END LOADED

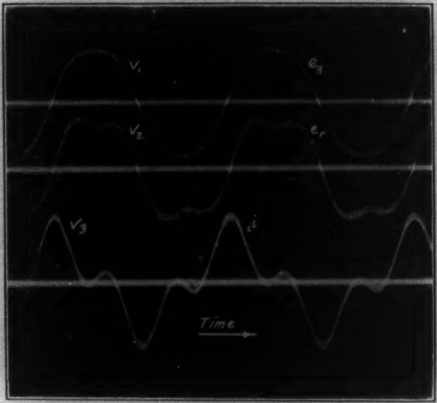
I_r = 0.92 amp. – Spacing 120 in. – f = 100 ~ – C = 2.96 mf. – L = 0.427 h. – E_g = 500 v. — E_r = 500 v. – I = 1.12 amp.



[MAGNUSSON AND BURBANK]

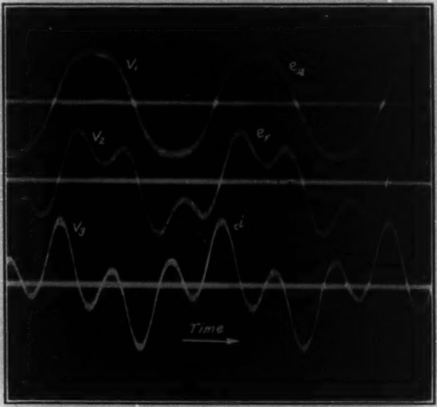
FIG. 27—RECEIVER END LOADED

Spacing 120 in. – f = 120 ~ – I_r = 1.01 amp. – L = 0.427 h. – C = 2.96 mf. – Eq = 500 v. – E_r = 500 v. – I = 1.21 amp.



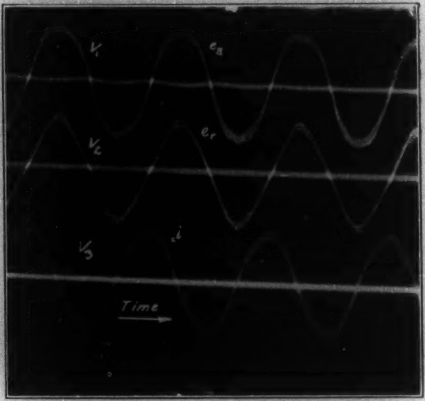
[MAGNUSSON AND BURBANK]

FIG. 29—RECEIVER END OPEN
Spacing = 96 in. – f = 60 ~ – C = 303 mf. – L = 0.412 h. – E_g = 500 v. – E_r = 570 v. – I = 0.70 amp.



[MAGNUSSON AND BURBANK]

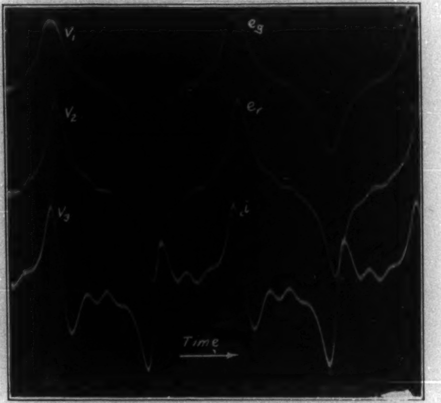
FIG. 30—RECEIVER END OPEN
Spacing = 96 in. – f = 74 ~ – C = 3.03 mf. – L = 04.12 h. – E_g = 500 v. – E_r =690 v. – I = 1.35 amp.



[MAGNUSSON AND BURBANK]

FIG. 31—RECEIVER END OPEN

Spacing 96 in. – f = 120 ~ – C = 3.03 mf. – L = 0.412 h. – E_g = 500 v. – E_r = 750 v. – I = 1.49 amp.

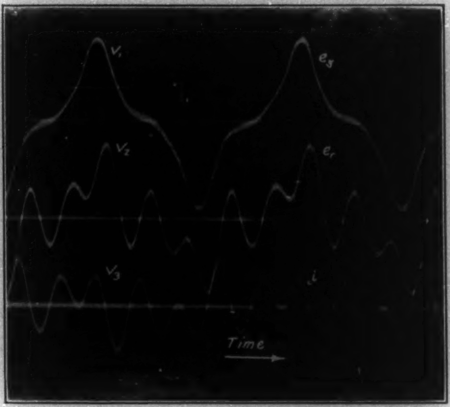


[MAGNUSSON AND BURBANK]

FIG. 34—RECEIVER END OPEN

Spacing = 96 in. – f = 25 ~ – L = 0.412 h. – C = 3.03 mf. – E_g = 2.50 v. – E_r = 260 v. – I = 0.20 amp.

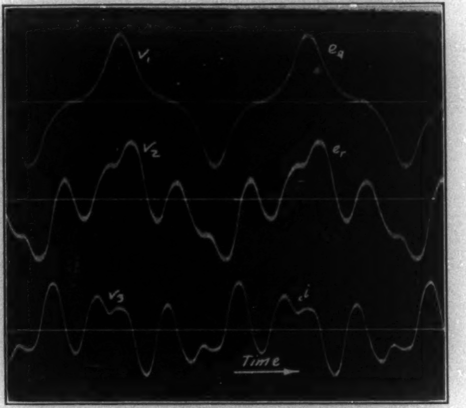
PLATE LXVIII.
A. I. E. E.
VOL. XXXV, 1916



[MAGNUSSON AND BURBANK]

FIG. 35—RECEIVER END OPEN

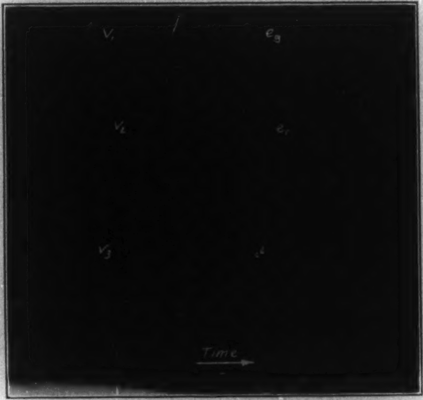
Spacing 96 in. – $f = 43.5 \sim$ – $C = 3.03$ mf. – $L = 0.412$ h. – $E_g = 250$ v. – $E_r = 420$ v. – $I = 1.00$ amp.



[MAGNUSSON AND BURBANK]

FIG. 36—RECEIVER END OPEN

Spacing 96 in. – $f = 50 \sim$ – $C = 3.03$ mf. – $L = 0.412$ h. – $E_e = 250$ v. – $E_r = 325$ v. – $I = 0.55$ amp.



[MAGNUSSON AND BURBANK]

FIG. 37—RECEIVER END OPEN

Spacing 96 in. – f = 72.5 ∼ – L = 0.412 h. – C = 3.03 mf. – E_g = 250 v. – E_r = 860 v. – I = 2.5 amp.

in Fig. 22, or at 72 cycles. The distortion is smaller at 100 cycles, Fig. 23, and practically disappears at 120 cycles, Fig. 24. The line constants give a resonance frequency of 222.2 cycles and hence for the third harmonic in resonance the fundamental frequency would be $\frac{222.2}{3} = 74$ cycles.

Similar oscillograms for a spacing of 96 in. (2.4 m.) and for frequencies of 60, 74 and 120 cycles are shown in Figs. 29, 30 and 31. The third harmonic is at a maximum for 74 cycles.

The dampening influence of the load on the receiver end is shown by comparing the voltage and current waves in Figs. 25, 26 and 27 with the wave shapes for the corresponding frequencies in Figs. 20, 23 and 24.

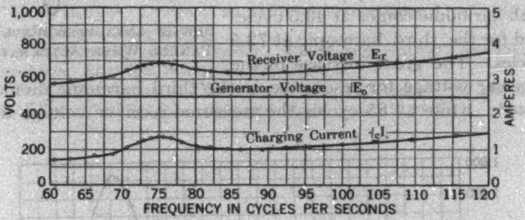


FIG. 28—RESONANCE CURVES WITH MACHINE GIVING NEARLY SINE WAVE AS SOURCE (ABOUT 1 PER CENT THIRD HARMONIC)

A much greater distortion is produced when using alternator *B*. The influence of the frequency for resonance conditions of both the third and fifth harmonics are shown in Figs, 34, 35, 36 and 37.

For 25 cycles, Fig. 34, the receiver voltage is practically of the same shape as the impressed voltage wave at the generator end. For 43.5 cycles the fifth harmonic produces resonance and causes a marked distortion of the receiver voltage. At 72.5 cycles, Fig. 37, the third harmonic is near resonance and the receiver voltage consists chiefly of the third harmonic. At 50 cycles, Fig. 36, the distortion of the receiver voltage is less than for either 43.5 or 72. 5 cycles.

Not only the wave shape but also the magnitude of the reeiver voltage is affected by the resonance of the harmonics in the impressed voltage wave. In Fig. 28 is shown the receiver voltage and charging current plotted as ordinates with the frequency of the impressed voltage from alternator *A* as abscissas. The voltage at the generator end of the line was held constant at 500 volts. The hump in the curve between 70 and 80 cycles is due to resonance produced by the third harmonic.

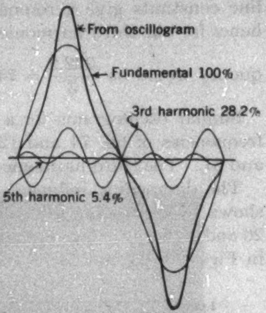


Fig. 32—Analyzed Wave of Peaked Wave Alternator

In Fig. 33, similar voltage and charging current curves are drawn for alternator *B*. The humps in the curves are produced by resonance in the line by the fifth and third harmonic.

The maximum point for the fifth harmonic comes at 43.5 cycles and for the third harmonic at 72.5 cycles. The great increase of the receiver voltage for resonance in the third harmonic should be noted; while at 85 cycles the measured receiver voltage drops to a comparatively low value, although considerably in excess of what would be produced by a simple sine wave.

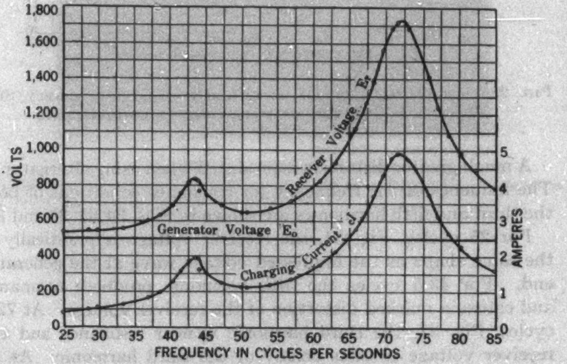


Fig. 33—Resonance Curves with Machine Giving Peak Wave, as Source—(5.4 per cent Fifth and 28.2 per cent Third Harmonic)

BIBLIOGRAPHY

1. W. S. Aldrich and G. W. Redfield. *The Performance of an Artificial Forty-Mile Transmission Line.* TRANS. A.I.E.E., XVIII, p. 339.

2. J. H. Cunningham. *Design, Construction and Test of an Artificial Transmission Line.* TRANS. A.I.E.E., XXX, p. 245.

3. J. H. Cunningham and C. M. Davis. *Propagation of Impulses over an Artificial Transmission Line.* TRANS. A. I. E. E., XXXI, p. 887.

4. A. E. Kennelly, Discussion. TRANS. A.I.E.E., XXXI, p. 190.

5. A. E. Kennelly and F. W. Lieberknecht. *Measurements of Voltage on Current Over a Long Artificial Transmission Line at 25 and 60 Cycles per Second.* Trans. A.I.E.E., XXXI p. 1131. Discussion p. 1164.

6. A. E. Kennelly and H. Tabossi. *Electrical World*, Feb. 17, 1912, p. 359.

7. A. E. Kennelly. The Distribution of Voltage and Current Over an Artificial Transmission Line in a Steady State. *Electrical World*, Aug. 10, 1912

8 A. E. Kennelly. A Convenient Form of Continuous-Current Artificial Line. *Electrical World*, June 14, 1913.

9. R. D. Huxley. Design of an Artificial Transmission Line. *Electrical World*, May 2, 1914, p. 980.

10. A. E. Kennelly and H. Pender. Resonance Tests of Long Transmission Line. *Electrical World*, Aug. 8, 1914.

11. C. E. Magnusson, J. Gooderham and R. Rader. A 200-Mile Artificial Transmission Line. *Electrical World*, June 12, 1915.

DISCUSSION ON "AN ARTIFICIAL TRANSMISSION LINE WITH ADJUSTABLE LINE CONSTANTS" (MAGNUSSON AND BURBANK), SEATTLE, WASH., SEPTEMBER 6, 1916.

L. J. Corbett: In connection with these artificial transmission lines, I presume that those of you who are familiar with the subject, recognize the two forms which have been in use for the last few years, the "distributed" type and the "lumpy" type. The more expensive is the distributed type, which is actually designed to correspond to a certain line. One of these, the first I believe, is the one at Schenectady. The wire is wound on glass cylinders with tinfoil on the inside surface. The cylinders are 4½ feet long (1.36 m.) and 6 inches (15 cm.) in diameter, and the length of line that each represents, is about one half mile. It would take a large room to hold a representation of a transmission line of even moderate size compared to some of our western lines. Another of this type was recently brought out at the University of California. You may be familiar with it. The cylinder was made of wood and the tinfoil was laid upon it; then followed a layer of insulation, then a layer of wire. The capacity was greater than in the Schenectady pattern, so smaller wire could be used, and the units were made to correspond to about ten miles of line. At the University of Idaho, we attempted approximately the same thing, using built up paper instead of wood cylinders. We modeled our line after one of the lines of the Washington Water Power Company, and constructed a unit which was to represent ten miles of line, but during that investigation, we found it rather unsatisfactory, because it was difficult to get the constants to correspond to the calculations. The variations in the wire might make our resistance vary a little, but we could adjust that by moving our contacts farther along the wire to get the proper value. The inductance also would vary slightly, but the greatest difficulty we had was in the capacity. With such a unit it was necessary to cut the tinfoil a great deal to avoid induced currents and have it with its sections not continuous around the cylinder. Even then the effect of eddy currents was so noticeable that the line would have a different capacity at one frequency from what it would have at another. So, it was practically impossible to get a really clear-cut set of constants on such a line. Another disadvantage of the distributed type is that after you once build your line, your constants are fixed. There is a great advantage possessed by this lumpy line described in the paper. While some do not approve of this type in general, because of the fact that it does not actually and accurately represent the transmission line, this one is adjustable so that it can be made to represent lines of various spacing, and by taking measurements between the units, a very true picture is obtained of conditions on the line at points ten miles apart. I would like to ask Prof. Magnusson how he maintains the frequency constant, or what instruments he uses to show the frequency if he does not use the vibrating reed.

W. D. Peaslee: I would like to ask Prof. Magnusson about this: Is it possible to pass enough current through the line—that is, load the line sufficiently—to use an ordinary laboratory synchronous generator as a synchronous condenser, and illustrate to the class the use of the synchronous condenser in maintaining the voltage drop constant under varying conditions of load. If it could be made of sufficient capacity to do that, without undue heating, that would be a very valuable addition to its use. The greatest value of a line of this kind is the ability with which you can reproduce a given line.

J. D. Ross: Dr. Magnusson's paper suggests an idea that is applicable to the larger central stations. The university faculties have been reaching out in the last few years to become more and more practical. All of us have observed that they have had considerable success in doing so, and I often wonder if the large central stations are reaching out on the technical end to the same extent. I do not believe they are. I think our testing work is often poorly arranged and under too many departments. We have, for instance, the testing of our distribution transformers under one man, our testing of inside construction under another. Hydraulic testing done by one man, and electrolysis by another, and the testing of meters, of course by a meter man. Probably the testing of meters properly belongs in the meter department. A properly constructed laboratory, constructed along the lines of all general testing as well as for special work, like this paper brings out, would be the proper way for a large central station to arrange this work. We have been promising ourselves an oscillograph for some time, and I think there will be a demand in our concern for an artificial transmission line such as Dr. Magnusson describes, especially at the small cost, comparatively, that he estimates. The way the most of us do now, instead of going at the cause of the trouble, and removing that, is to try to find a partial cure. When a surge comes, on our lines or we repeatedly have trouble, we attempt to put on some apparatus that may cure them rather than find their cause and take them away altogether. The method we have been following, for instance, with the trouble we have had with surges in our high-tension work is really a cut and try method.

I believe that a well equipped testing laboratory with the testing of a large concern all put under it, would yield better economy in the end than our present system. Of course, it would all come back to the question how technical and practical the man in charge would be. He would have to be a very good man to get good results, but there are such men, and I think most large concerns have three or four of them that they can pick from for that particular work. Apparatus of the sort mentioned here would be of considerable value in connection with our troubles if it was in the hands of a competent man. An example, which, is of course, on a larger scale than any of us can reach, is the laboratory of the General Electric Company. Those of you who have read the papers from the *General Electric Review* lately can see the remarkable work they have done. The work should not all be left to the universities. While they are reaching out to be practical, every large plant should reach out to be technical at the same time.

S. R. Burbank: I want to speak strictly from the student's standpoint. This work was exceedingly interesting to me, and I know that it was to other students. The way in which the work checked with the theory was of great interest. One point of particular interest was the shape of the curve, in Fig. 33, referred to by Dr. Magnusson. When the frequency at which the first hump occurred is multiplied by five, and that of the second hump by three, the same frequency is obtained, and checks the theoretical surge frequency calculated from the line constants. We would like to have obtained the hump for the fundamental, but the machine would not stand the necessary speed.

C. A. Whipple: I believe there is a use for these artificial power lines outside of the universities. I believe that in practise, we can find them of great usefulness. On several occasions I have found it somewhat difficult to persuade a board of directors or a city council that certain things were necessary for the proper operation of their system. By having such equipment as described here available, they could, possibly, by their own observations, have been convinced that such was the fact. I have an instance in mind, where a certain body of men had called me in to report to them upon the feasibility of purchasing a certain piece of equipment to correct and economize their existing power system. I told them they were wasting their money absolutely, but the salesman from the manufacturing company gave a very brilliant talk, and they finally purchased that machine. I visited the place three months after it was installed, and it was standing there idle, absolutely useless. They could have bought a dozen of the models described here for the money they wasted in that one mistake. I believe that frequently, capitalists and those handling the financial end of the transactions, who will not look to the engineer for advice, can be persuaded by such a means as this.

C. E. Magnusson: Answering the question asked by Mr. Corbett, I will state that we used a standard electric frequency meter, which consists of a magneto or constant magnet generator connected to a millivolt-meter. The vibrating reed has altogether too large a variation between the successive indicating reeds.

In reply to Mr. Peaslee, you may note from the curves in the paper that the current was about one ampere or 1.5 amperes in some cases. I do not recall that the coils showed any appreciable rise in temperature. The coils are made of No. 14 wire, and are not very thick. I think they cool at least as readily as the fields of an ordinary motor, and a higher voltage could readily be used. In fact, the only reason for using only 500 volts was that this was sufficient for the purpose of this test. The condensers were rated at 1000 volts each and a much higher voltage could be used. As you will notice, we have a spark gap on each unit. This was found necessary in order to protect the condensers during resonance conditions.

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CHARACTERISTICS OF ADMITTANCE TYPE OF WAVE-FORM STANDARD

BY FREDERICK BEDELL

Abstract of Paper

It is generally agreed that a sine wave of electromotive force at generator terminals and on transmission lines is best. A sine wave is now specified as standard by the Standardization Rules of the Institute, but the present methods for prescribing allowable limits and for determining how near an actual wave is to a true sine wave are very unsatisfactory. The Standards Committee, through a sub-committee, is studying the subject in order to ascertain whether a standard can be specified that will be more suitable in its characteristics and more practical in its application. As a contribution to this study, the characteristics of a certain type of standard are here set forth.

It is hoped that various points of view and much information may be brought out in discussion, which may be on the general subject and not limited to the particular phase discussed in the paper.

Introduction

ALTHOUGH in certain respects a departure from a sine wave of electromotive force at generator terminals or on a transmission line may not be objectionable, it has been found that in most respects such a departure is objectionable to a very high degree; the sine wave is, therefore, the generally recognized standard or ideal that all desire to see approached more and more closely as the art of electrical engineering progresses. The troubles that are caused by a departure from a sine wave depend to a considerable extent upon the frequency of the harmonic or harmonics which are present in the wave in addition to the pure sine wave of fundamental frequency. For example, harmonics of a certain more-or-less low range of frequencies cause trouble in the parallel operation of machinery, while harmonics of a somewhat higher range cause trouble by inductive interference with neighboring telephone circuits. In penalizing therefore, a departure from a sine wave, it becomes necessary either to penalize all harmonics equally, or to endeavor to make the penalty fit the crime and to prescribe different penalties to the various harmonics, which are present in addition to the fundamental, according to their frequencies.

The present Standardization Rules of the Institute, after stating that the sine wave shall be considered standard, specify the manner (Rule 406) by which the so called "deviation" from a sine wave shall be measured. This measure of deviation has been found generally unsatisfactory, not only because it involves expensive special apparatus (commonly an oscillograph) and the services of a man expert in such work, but also because even in the hands of an expert the numerical results are not directly obtainable, being found only, after a kind of cut-and-try or juggling process.

On account of these objections to "deviation" as a practical measure of wave distortion, there was introduced Rule 17*, which defines distortion factor without specifying the numerical value that will be allowed. It was doubtless felt that experience was needed before specifying such a numerical value; but experience has shown objections to a distortion factor as defined in Rule 17, as will be pointed out later. Meanwhile the objectionable "deviation" rule, which all hope may soon be superseded, still persists.

The question of a standard for wave shape has been discussed† before the Institute on several occasions, and during the past year has been the subject of study of a sub-committee‡ of the Standards Committee. This paper describes certain work done in connection with the work of this sub-committee. It is not intended to be complete, nor to present conclusions, nor to commit the members of the committee in any way. Its object is to bring the matter to the attention of those interested, with a view to obtaining, through discussion or correspondence, different points of view and, so far as possible, to ascertain all the facts bearing on the matter. It is felt that to attempt to standardize wave form with our present knowledge would be premature. There are so many sides to the question, and the interests involved are so diverse, that it is only through wide spread interest and discussion that all the facts and all the aspects of the case can be brought out. The scope of this paper is limited to the characteristics of a certain type of standard but the discussion may be more general.

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*Rule 17. The Distortion Factor of a Wave. The ratio of the r.m.s. value of the first derivative of the wave with respect to time, to the r.m.s. value of the first derivative of the equivalent sine wave.

†A *Proposed Wave Shape Standard*, by C. M. Davis, TRANS. A. I. E. E., p. 775, Vol. XXXII, 1913; discussion, pp. 831-845. Three papers on *Irregular Wave Forms*, by F. Bedell and others, presented at Deer Park, 1915, TRANS, A. I. E. E., Vol. XXXIV, p. 1135.

‡ Messrs. L. W. Chubb, F. M. Farmer, H. S. Osborne, L. T. Robinson and F. Bedell, Chairman. Aid in the preparation of this paper, and in experiments not here reported, has been obtained from Messrs. A. Bailey, R. Bown, G. E. Grantham, W. G. Mallory and P. T. Weeks.

ADMITTANCE STANDARDS

Of the various factors that have been discussed before the Institute for defining the distortion of an alternating wave, the differential distortion factor, (which is the distortion factor of Rule 17, as given above) meets the requirements of a commercial standard perhaps better than any other.

For practical purposes this factor can be defined in terms of the admittance of a condenser as follows:

> (*Condenser Admittance Standard.*) The distortion factor of an e.m.f. wave is the ratio of the admittance of a condenser supplied with that wave at its terminals to the admittance of the same condenser when supplied at its terminals with a sine e.m.f. of the fundamental frequency.

The objections to the condenser standard are three-fold: *First*, the wave form of the alternator under test may in some cases become distorted by the condenser used in making the test on account of resonance between the condenser and the inductance of the armature. (This resonance would be for some particular harmonic component of the alternator wave and this component would be unduly magnified so as to distort the e.m.f. form.) *Second*, the penalizing of lower harmonics is too little and of higher harmonics is too great. *Third*, for accuracy the condenser circuit must contain capacity only; hence any resistance or inductance of the ammeter used to measure condenser current introduces error.

These objections, however, can all be eliminated, if certain modifications are made in the definition of the standard and in the method of test; in this way a more practical and a more desirable working standard can be obtained. There are several ways in which these modifications can be made, leading to several possible wave form standards that will now be discussed.

As is well known the admittance of *any* circuit, or combination of circuits, containing inductance or capacity varies with the wave form of impressed voltage and with the fundamental frequency, so that, for a given fundamental frequency, the admittance of a specified circuit is an indication of the wave form of voltage impressed at its terminals and may be taken as a measure of wave distortion.

A general definition of distortion factor, in terms of the admittance of some standard circuit, is, accordingly, as follows:

(*General Admittance Standard.*) The distortion factor of an e.m.f. wave is the ratio of the admittance of a specified standard circuit supplied with that wave at its terminals to the admittance of the same circuit when supplied at its terminals with a sine e.m.f. of the fundamental frequency.

Special cases arise according to the standard circuit specified. A condenser standard (giving the differential distortion factor, δ) and an inductance standard (giving the integral* distortion factor, σ) are seen to be special cases.

Any one of a limitless number of possible circuits might be specified as a standard, and each would give a distortion factor with certain characteristics of its own, as in the particular cases of δ and σ.

Circuits that might be taken as standard can be classified under two heads:

I. *Simple Standard Circuit*, in which resistance, inductance and capacity (or any one or two of them) are arranged in series and are given specified relations or values.

II. *Composite Standard Circuit*, in which the component parts are arranged in other than simple series arrangement.

A simple standard has the obvious advantages of simplicity; it is possible for the testing engineer to check up the standard or to duplicate it with apparatus commonly available. The significance of the standard and the results obtained can be readily grasped and the standard has, to a certain extent at least, a rational rather than an arbitrary basis. A composite standard, on the other hand, has the advantage that it offers a greater range of possibilities in the weighting of harmonics of different frequencies.

A simple standard itself offers great range in the weighting of harmonics, as will be brought out later, but, if no one of these possible weightings comes sufficiently near to the requirements of the case, it may be preferable to abandon the advantages of simplicity and to adopt a composite standard, provided that one is found that is so distinctly superior in its weighting as to make its adoption worth while.

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*See Deer Park papers, *loc. cit.*

A standard circuit consisting of resistance only would be impossible, for the admittance of such a circuit does not vary with wave form. A standard consisting of an inductance only would be impracticable (even were it desirable), for the admittance on any commercial wave would differ so little* from the admittance on a sine wave that the difference could scarcely be determined. For the same reason, a circuit consisting of *R* and *L*, combined, would be impracticable. Furthermore, a circuit consisting of *L* and *C* with no resistance (were this possible) would be unsuitable as a standard, for it would prohibit absolutely the existence in an alternator of an harmonic of a particular frequency; for acceptance of an alternator, the allowable value for the harmonic of the frequency at which *L* and *C* were in resonance would be zero, as seen later in connection with the curve marked "$R = 0$" in Fig. 2.

This leaves as possible the condenser standard, the *R C* standard (which is the condenser standard with some resistance added in series) and the *R L C* standard (which is the condenser standard with some resistance and inductance added in series). In all these cases the condenser is the predominant element, that is there would be but a small difference between condenser voltage and line voltage.

The condenser standard, without resistance, gives a chance for error in measurement (due to resonance between the condenser and armature inductance) as already pointed out. This error, however, may be reduced and practically eliminated by the introduction of resistance. We have, then, to choose between the *R C* standard and the *R L C* standard, and the choice between these two should be made after comparing the characteristics of each. It is to be noted that the presence of *R* and of *C* is essential; whereas the inductance† is not necessary, being added or not according to the characteristics that may be found desirable.

The accompanying curves show the characteristics for various standard circuits. The ordinates for each curve show the relative amplitudes that are allowed by the various standards for harmonics of different frequencies, it being assumed in all cases that no more than one harmonic is present. The mathematical relations on which these curves are based are given in Appendix I.

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*This difference is only a fraction of one per cent; thus, if the admittance of an inductive circuit on a sine wave is unity, it is 0.9952 on a wave having a fifth harmonic of ten per cent in addition to the fundamental.

†Inasmuch as the *RC* standard should be free from inductance, a small error is introduced by inductance in the ammeter; with the *RLC* standard this error may be avoided by including the inductance of the ammeter as part of the inductance of the standard circuit.

As a basis for comparison, a curve for the condenser standard is shown by the dotted curve in each figure. The scale of ordinates is relative, the absolute values depending upon the specified value for the distortion factor. Thus, for the dotted curves, a distortion factor 1.12 allows a fifth harmonic equal to 10 per cent, of the fundamental, a seventh harmonic equal to about 7¼ per cent., etc., the allowable amplitude decreasing* with the order of the harmonic. The fifth harmonic is marked for convenient reference. The value of the fifth harmonic, E_5, for different values of distortion factor, δ, are as follows:

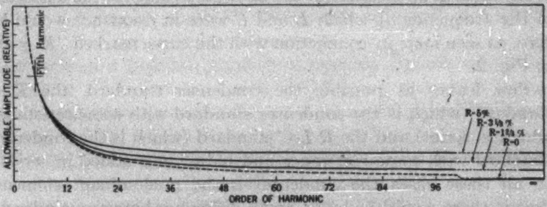

FIG. 1. *RC* standard, resistance being 1 2/3 per cent, 3 1/3 per cent and 5 per cent of reactance of condenser at fundamental frequency. The curves approach, $E_\infty = 5\,E_5\,\dfrac{R}{X_1}$ (approx.) at infinite frequency. Dotted curve is condenser standard.

E_5	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12
δ	1.02	1.03	1.045	1.06	1.08	1.10	1.12	1.145	1.17

The scale for the curves is thus determined in terms of distortion factor.

In Fig. 1, the solid curves show the characteristics of the *R C* standard for three different values of *R*, namely, 1⅔, 3⅓ and 5 per cent of condenser reactance at fundamental frequency. These curves approach the limiting minimum value,

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*The amplitude varies (approximately) inversely as the order of the harmonic. If k is the order of the harmonic,

$\delta = (1 + k^2 E_k^2)^{\frac{1}{2}} \div (1 + E_k^2)^{\frac{1}{2}}$, as derived in Appendix I. The denominator $(1 + E_k^2)^{\frac{1}{2}}$ differs from unity by less than half of one per cent, if E_k is not over 0.10. Substituting unity for the denominator, we have then, with an error of less than half of one per cent,

$\delta = (1 + k^2 E_k^2)^{\frac{1}{2}}$, or $E_k = (\delta^2 - 1)^{\frac{1}{2}} \div k$. For constant δ, E_k accordingly varies inversely as k, the dotted curve being an hyperbola.

$$E_\infty = 5\ E_5\ \frac{R}{X_1}, \text{ approximately.}$$

The RC standard is practically free from the objections given for the condenser standard and it is readily assembled from apparatus commonly at hand. In this respect it is superior to the $R\ L\ C$ standard and, from the standpoint of practicability,* is the most satisfactory working admittance standard. Whether its characteristics are more or less desirable than those of the $R\ L\ C$ standard is a question to be determined; these latter characteristics will now be discussed.

The current flowing through an $R\ L\ C$ circuit at constant voltage increases with frequency until resonant frequency is reached and then decreases, as is discussed in various text books.† In the case of a distorted wave, the current produced by a particular harmonic varies in a like manner, a fact that has been made use‡ of in the determination of the amplitudes of the harmonics to which distortion is due. In the use of such an $R\ L\ C$ circuit as a standard, it is not necessary, however, to go so far as to determine the numerical values of the harmonics that may be present, but merely to make sure that the harmonics do not exceed certain specified values.

The curves in Fig. 2 show the characteristics for an $R\ L\ C$ standard and correspond to the curves shown in Fig. 1 with the addition of a certain inductance, so that L and C are resonant at a particular frequency, in this case 1500 cycles. Except for the inductance, the circuits for the curves in Figs. 1 and 2 are identical. It is seen that, in Fig. 2, the curves come to a definite minimum $\left(\text{approximately } 5\ E_5 \frac{R}{X_1}\right)$ at the resonant frequency instead of at infinite frequency, as in Fig. 1; this minimum value is determined by and is directly proportional* to the resistance.

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*With the possible exception of the effect produced by ammeter inductance.

†See, for example, Fig. 32, "Alternating Currents" by Bedell and Crehore, 1892.

‡See "Analysis of E.M.F. Waves," by P. G. Agnew, *Bul. Bureau of Standards*, p. 95, Vol. VI., 1909, where the use of a series *RLC* circuit is described; for another arrangement, see articles by M. I. Pupin, *Am. Journ. Sc.*, pp. 379, 473, 1894. Resonant circuits have also been used to determine harmonic currents that are present in addition to direct current in trolley circuits.

It will be seen that by selecting the values to be specified for distortion factor, and for R and L in the standard circuit, the characteristics of the $R\ L\ C$ standard can be adjusted to a wide range of conditions. The minimum of the curve, which is the point of maximum penalty, has its position (*i.e.*, the frequency at which it occurs) determined by L; its relative value determined by R. The absolute value of the scale, for the whole, curve, is determined by the specified distortion factor.

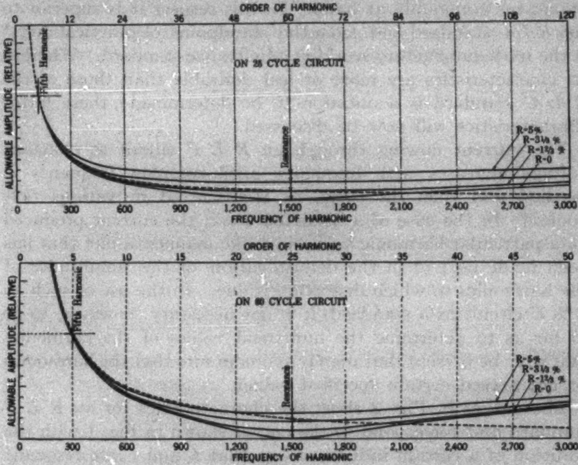

FIG. 2. *RLC* standard; resonance at 1500 cycles. Resistance is 0, 1 2/3 per cent, 3 1/3 per cent and 5 per cent of reactance of condenser at fundamental frequency. E at resonance $= 5\, E_5 \dfrac{R}{X_1}$ approx. (On 25-cycle circuit, R is 1, 2 and 3 times reactance of condenser at resonant frequency. On 60-cycle circuit, R is 0.41, 0.83 and 1.25 times reactance of condenser at resonant frequency.) Dotted curve is condenser standard.

It will be noted that no changes in the values of $R\ L$ or C affect materially any of the curves for the lower harmonics, the allowable values for the lower harmonics being determined solely by the specified value for distortion factor. For the lower harmonics, the dotted curve for the condenser standard is seen to coincide practically with the solid curves of the *R C* and the *R C L* standards. It is thus seen that the constants of the circuit have a material effect only on the values of harmonics of the middle and higher ranges.

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*This is very close to a true proportionality for all practical cases; the departure from proportionality only occurs when the amplitude of the harmonic is much more than is generally found in practise.

Fig. 2 shows the effect of varying *R* when *L* is constant.

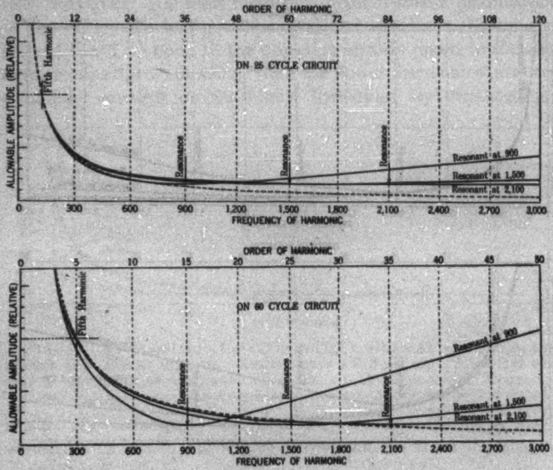

FIG. 3. *RLC* standard; resonance at 900, 1500 and 2100 cycles. Resistance is 3 1/3 per cent of the reactance of condenser at fundamental frequency. Dotted curve is condenser standard.

(It is understood that these values are not absolute but are relative to the value of *C*.) The intersection of the dotted curve with one of the solid curves at resonance is due to the fact that in this case the resistance had a value equal to the reactance of the condenser at resonance, a relation discussed further in connection with Fig. 4.

Fig. 3 shows the effect of varying *L* when *R* is constant. Three values are taken for *L* giving resonance at frequencies of 900, 1500 and 2100. A rapid rise in the curve after the minimum is reached is objectionable in a standard, and this is seen to be the more marked the lower the resonant frequency.

In Figs. 2 and 3, the value of R is specified in terms of the reactance of the condenser at fundamental frequency, and accordingly is different for 25- and 60-cycles circuit. As a result, the ordinates of the 25-cycle and 60-cycle curves are equal at resonant frequency; the amplitude of harmonic allowed is thus constant at this absolute frequency, irrespective of the order of the harmonic with respect to fundamental frequency.

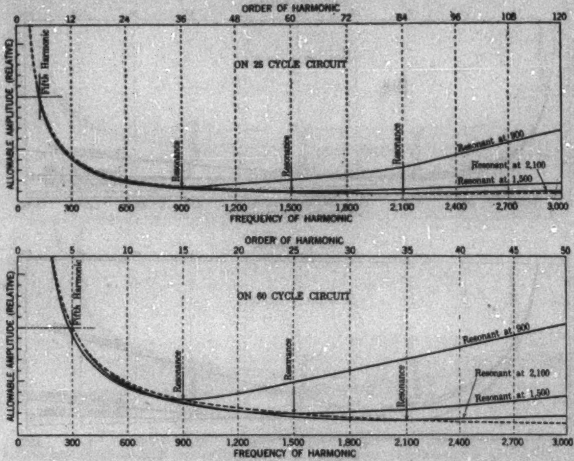

FIG. 4. *RLC* standard; resonance at 900, 1500 and 2100 cycles. Resistance is equal to reactance of condenser at resonant frequency, irrespective of fundamental frequency. Dotted curve is condenser standard.

Fig. 4 shows the characteristics of the *R L C* standard when R is constant, irrespective of the frequency of the circuit, R being equal to the reactance of the condenser at resonant frequency. Curves are drawn for three resonant frequencies. It is seen that in each case, in Fig. 4, the curves closely follow the dotted curve of the condenser standard up to the resonant point. Up to this point, each curve lies just below the curve for the condenser standard, thus imposing a slightly greater penalty on harmonics through this range.

Although it is more logical for the value of R to depend upon fundamental frequency, there would be an obvious practical advantage in having R constant, irrespective of fundamental frequency, for all circuits. If R were made equal to the condenser reactance at resonant frequency, there would be a further advantage that the resonant distortion factors thus defined differ little in numerical value from the present (differential) distortion factor, the solid and dotted characteristic curves, in Fig. 4, following each other closely up to the point of resonance, where they intersect; resonant distortion factor is then a modification of the distortion factor of the condenser standard. But such a factor would be open to the objection already raised to the condenser standard, namely, that the lower harmonics are not penalized enough or the higher harmonics are penalized too much. By increasing the value of R, the solid curves in Fig. 4 would be raised in the region of resonance in the same manner as in Fig. 2.

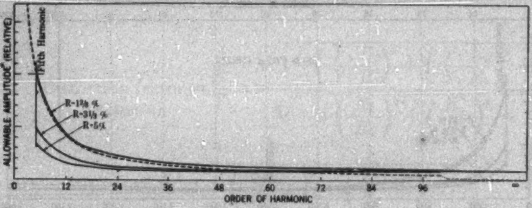

FIG. 5. RC standard; the same as Fig. 1 with scale changed so that curves coincide at infinity. Resistance is 1 2/3 per cent, 3 1/3 per cent and 5 per cent of reactance of condenser at fundamental frequency.

It is to be kept in mind that any change in R affects only *relative* values of the allowable harmonics at different frequencies, provided the appropriate numerical value is assigned to the distortion factor.

A comparison of Figs 5 and 6 with Figs 1 and 2 may make this clearer. Each curve in Fig. 1 is drawn for the same value of distortion factor, this causes the curves to practically coincide at low frequencies (irrespective of the value of R) and to diverge at high frequencies. The curves of Fig. 1 are redrawn in Fig. 5, each for a different value of distortion factor, so that they coincide at infinite frequency and diverge at low frequencies. In a like manner, the curves of Fig. 2 are redrawn in Fig. 6, with different values of distortion factor, so as to coincide at resonant frequency.

From the foregoing study it will be seen that an increase in R decreases the penalizing of the high harmonics *relative* to the low (or increases the penalizing of the low harmonics relative to the high), the absolute value of either high or low being not necessarily affected.

It should be noted that an increase in resistance tends to decrease the sensitiveness of measurement; thus, in Fig. 5 or 6, the distortion factor might be changed from, say, 1.17, with the smaller resistances, to about 1.05 and 1.02, respectively with the larger resistances.

If a standard of the admittance type is deemed desirable, there are many points to be decided before the exact specification of the standard can be determined. Some of these points are as follows:—

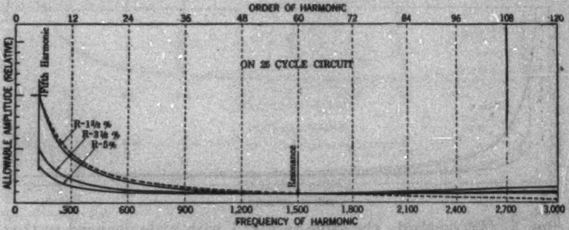

FIG. 6. *RLC* standard; the same as Fig. 2 with scale changed so that curves coincide at resonant frequency. Resistance is 1 2/3 per cent, 3 1/3 per cent and 5 per cent of reactance of condenser at fundamental frequency, or 100 per cent, 200 per cent and 300 per cent of reactance of condenser at resonant frequency.

1. Shall the standard circuit be a simple circuit, as described in this paper, or a composite circuit?

2. If a simple circuit is to be adopted, shall this circuit contain an inductance and, if so, how much; or, in other words, what shall be the resonant frequency?

3. How much resistance shall the standard contain; should this resistance be different for circuits of different frequencies, or should it be the same for all frequencies?

4. What numercial value of the factor thus specified should be allowed in acceptance of alternators?

5. What details and what load conditions conducting tests should be specified?

APPENDIX I

FORMULAS FOR DISTORTION FACTORS

An irregular voltage wave, composed of a fundamental E_1 and harmonics E_3, E_5, E_7, etc., has a r.m.s. value

$$E = (E_1^2 + E_3^2 + E_5^2 + \ldots)^{1/2}$$

If Y_1, Y_3, Y_5, etc., are the admittances of the standard circuit for the fundamental and for the several harmonics, respectively, the current taken by the standard circuit when subjected to the irregular voltage E, is

$$I = (E_1^2\, Y_1^2 + E_3^2\, Y_3^2 + E_5^2\, Y_5^2 + \ldots)^{1/2}.$$

The admittance of the standard circuit on the irregular wave is I/E; its admittance on a sine wave is Y_1. The former divided by the latter gives

$$\text{Distortion factor (general)} = \frac{\frac{I}{E}}{Y_1} = \frac{\sqrt{1 + \left(\frac{Y_3\, E_3}{Y_1\, E_1}\right)^2 + \left(\frac{Y_5\, E_5}{Y_1\, E_1}\right)^2 + \ldots}}{\sqrt{1 + \left(\frac{E_3}{E_1}\right)^2 + \left(\frac{E_5}{E_1}\right)^2 + \ldots}}$$

$$= \frac{\sqrt{1 + \left(\frac{Y_3}{Y_1} E_3\right)^2 + \left(\frac{Y_4}{Y_5} E_5\right)^2 \ldots}}{\sqrt{1 + E_3^2 + E_5^2 + \ldots}}$$

In this last equation, E_1 has been taken as unity.

When only one harmonic of order k is present

$$\text{Distortion factor} = \frac{\sqrt{1 + \left(\frac{Y_k}{Y_1} E_k\right)^2}}{\sqrt{1 + E_k^2}}$$

All the curves in this paper are determined by this equation, by giving a constant value to distortion factor and determining E_k for different values of k.

The preceding equations are general and apply to any standard circuit. For the particular case of the condenser standard, $Y_3/Y_1 = 3$, $Y_5/Y_1 = 5$, etc.; hence

$$\delta = \frac{\sqrt{1 + (3\,E_3)^2 + (5\,E_5^2) + \ldots}}{\sqrt{1 + E_3^2 + E_5^2 + \ldots}}$$

When only one harmonic is present,

$$\delta = \frac{\sqrt{1 + (k E_k)^2}}{\sqrt{1 + E_k^2}}$$

This equation may be used in determining the dotted curves in Fig. 1 to 4.

APPENDIX II

MEASUREMENTS

It has not been the object of this paper to discuss at length experimental details, nor to bring up various questions relating thereto. A brief statement concerning test methods will, however, not be out of place.

The admittance of a standard circuit, when supplied at its terminals with the voltage under test, is readily determined by ammeter and voltmeter readings. Unless an electrostatic voltmeter is used, the ammeter should be included as part of the standard circuit, the resistance and inductance of the instrument (unless negligible) being included in the specified values of R and L for the standard.

The admittance of the standard circuit on sine-wave voltage may be determined either by calculation or by voltmeter and ammeter readings when sine voltage is impressed at the terminals of the standard.

In the former case, it is necessary to know accurately the absolute values of $R\,L\,C$ and frequency, and also the absolute values of the current and voltage in the determination of admittance on the irregular wave. Great care is therefore necessary to insure dependable results.

In the latter case the value of I/E on the irregular wave, divided by I/E on the sine wave gives the distortion factor. It is seen that in this case only relative values are necessary, as the result is a ratio; fairly accurate results can be obtained even with rather crude instruments, provided, of course, that the readings on the irregular wave and the sine wave are both taken with the same ammeter and voltmeter.

A sine wave sufficiently pure for the purpose can be derived from the irregular voltage wave by augmenting the fundamental and choking out the harmonics. One way* for accomplishing this that has been found satisfactory is to place in parallel with the standard circuit a condenser C' having a capacity preferably much larger than the capacity of the condenser in the standard (say five times as large) and to place a non-ferric inductance L' in series with the combination of C' and the standard circuit in parallel. The inductive reactance of L' at fundamental frequency should be greater (say at least 25 per cent greater†) than the capacity reactance of C' at fundamental frequency. With suitable switches, the ammeter and voltmeter readings giving the admittance first on the irregular wave and then on the sine wave are readily taken; the ratio gives the distortion factor.

The numerical values of distortion factor with the $R\,C$ or $R\,L\,C$ standard will differ but little from the value of differential distortion factor δ, particularly when R and L are specified with a view to making this difference small. To do this may be worth while, in view of the fact that δ is a constant of definite theoretical significance and of use in certain calculations.‡

It may be pointed out that the measurement of $\delta\,\sigma$ by the split dynamometer method, referred to in one of the Deer Park papers, is also practically a measurement of δ, inasmuch as the value of σ is so nearly unity,—more than 0.995 in most cases. (For this reason certain objections to the condenser or δ standard hold as well for the $\delta\,\sigma$ standard.) The dynamometer reading varies as the product of the current in the two windings. The current in one winding is derived through a condenser reactance and is proportional to $\delta / C\omega$; the current in the other winding is derived through an inductive reactance and is proportional to $L\omega$. The product is proportional to $\delta\,\sigma$ and is independent of frequency. The reading of the instrument is, however, dependant upon voltage. By substituting suitable resistances for the reactances, the reading of the instrument with reactances in circuit divided by the reading with resistances in circuit gives the value of $\delta\,\sigma$ irrespective of voltage or fre-

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*This is essentially the method by which a sine wave has been obtained for the Ryan Cathode Ray Oscillograph; see TRANSACTIONS, A. I. E. E., p. 539, Vol. XXII, 1903.

The Davis method (*loc. cit.*) is a particular case in which $C = 0$. The presence of C' reduces the size of L' and gives a resultant sine wave with greater accuracy when the standard contains R and L as well as C.

†Strictly speaking, it must be greater than the joint reactance of C' and C in parallel. It should be enough greater to make *sure* that it is greater and to avoid instability of readings that may occur when inductive reactance and capacity reactance are nearly equal.

‡See Mizushi paper, Deer Park, *Loc. cit.*

quency. Variations of voltage and frequency even as much as 100 per cent have been found tolerable.

The dynamometer wave-form meter has been made more sensitive by a differential arrangement, two dynamometers being mounted on one moving system, the two coils of one dynamometer deriving current through inductive and condenser reactances, respectively; the two coils of the other, through resistances. The simpler single split-dynamometer has, however, been found by the writer to be sufficiently sensitive.

Theoretically the split dynamometer gives true values of $\delta\,\sigma$ only when the two reactances have zero resistance, a condition that can be approached but not exactly obtained. By putting resistance or resistance and inductance in series with the condenser, it might be possible to make the readings of the instrument approximate the distortion factor of the $R\,C$ or $R\,L\,C$ standard, but these possibilities have not been investigated.

DISCUSSION ON "CHARACTERISTICS OF ADMITTANCE TYPE OF WAVE-FORM STANDARD" (BEDELL), SEATTLE, WASH., SEPTEMBER 8, 1916.

Joint Committee on Inductive Interference: The importance of wave-form as a factor in determining the extent of inductive interference with telephone service resulting from cases of parallelism of power and telephone circuits, has been pointed out on several occasions by this Committee and by others. Its supreme importance from our point of view renders particularly desirable the adoption of a suitable method of measurement and the enforcement of the lowest practicable limiting value of distortion of wave forms of rotating machinery measured by such standard. We have had occasion to take this matter up with the Standards Committee of the Institute and are glad to note the interest manifested by the Standards Committee in undertaking a study of the subject through the appointment of a subcommittee, whose Chairman is the author of the paper under discussion.

In principle, an admittance standard for determining the distortion factor of an e.m.f. wave appears to be eminently suitable from our point of view and has a great advantage over methods which require a tedious analytical or cut-and-try process. As to the specific type and constants of an admittance standard and the numerical value of the distortion factor which should be taken as a limit, our present information does not warrant us in making a recommendation.

The first and most difficult problem to be solved before settling upon a particular circuit to be employed in measuring the distortion of wave form is to determine the law expressing the relative detrimental effects of different harmonics in a machine wave-form under representative conditions of operation. This involves, besides a knowledge of the variation with frequency of the damage due to induced current in a telephone receiver (physiological effect), a consideration of the distortion of wave form of voltages and currents which takes place between the telephone receiver and the rotating machinery of the power system. Doubtless somewhat arbitrary assumptions will have to be made in evaluating many of the facts, lines in the chain between telephone receiver and generator. However, every effort should be made to determine this law, in order that the relative interference-producing powers of various machine wave forms may be known. Only through this knowledge can improvement over present conditions be most economically made. Given the law expressing the relative importance of the different harmonics in a machine wave form, if the matter of inductive interference is to govern (and we believe it to be the most important consideration usually involved and the one requiring the most rigid limitation of harmonics) the variation with frequency of the admittance of the standard selected should follow this law as closely as practicable. Though our present information on this subject is not complete, it indicates that a standard penalizing the higher harmonics to a greater degree (relative to low harmonics) than the condenser standard is desirable. This apparently requires a composite circuit, rather than one of the simple circuits described in Dr. Bedell's paper. It seems to us that the disadvantages of a complex circuit are to be regarded as of minor importance. If it is impracticable at this time to determine the relative weights which should be assigned to the different harmonics and to prescribe a composite circuit which would weight the harmonics exactly as desired, we recommend the condenser standard as being far superior to the present or "deviation" standard.

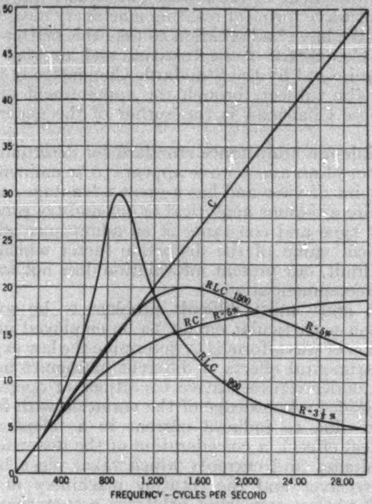

Fig. 1

It is well to note the fact that the curves and discussion given in the paper are based on the assumption of a single harmonic, whereas several are usually present. Possible misinterpretation of the plots on this account could be avoided by plotting "relative penalty" curves, which would apply regardless of the number or amplitude of the harmonics present. In keeping with the designation of the type of standard, the ordinates would be directly proportional to the admittance of the circuit and the curves for the condenser standard become straight lines. Fig. 1

shows several curves plotted on this basis. They are approximately reciprocal to the curves given in the paper for circuits with the same constants.

With respect to the five questions at the close of Dr. Bedell's paper:

1. As discussed above, a composite circuit is probably desirable.
2. If a simple circuit is to be adopted, the inductance should be such that the circuit does not resonate below 1500 cycles.
3. The resistance in the simple circuit should be as small as possible.
4. The numerical value of the factor would have to be determined after careful consideration of present practise and opportunities for improvement in design. It is possible that alternators of different types and ratings should be classified in different groups and different factors specified for each group. For example, small, slow-speed, high-voltage synchronous motors might be allowed a greater factor than large turbine-driven generators, for the reasons that the wave-form of an extensive network is generally less affected by a small motor than by a large generator, and the suppression of harmonics is more difficult in the former than in the latter class of machines.
5. As it is the wave form under load conditions in which one is primarily interested, and as this is different from the no-load wave form, tests should be conducted, as far as practicable, under conditions simulating those under which the machines will operate. We realize the difficulty of so doing in many instances.

Apart from the consideration of an admittance standard for determining the distortion of machine wave form, there may be a field for an admittance type of standard in determining the equivalent "noise-volts" in telephone conductors subject to inductive interference.

H. S. Osborne: Prof. Bedell has pointed out that the selection of a wave-shape standard involves two general problems:

1. What shall be the relative amounts permitted of components of different frequencies.
2. What numerical values shall be set under different conditions to the standard thus defined.

From the standpoint of inductive interference in telephone circuits, the relative weighting of harmonics of different frequencies is of importance both in connection with the consideration of wave-shape standards and for practical use in the investigation of induced noise in telephone circuits, particularly in considering the relative effect of different generators or other electrical machinery in producing interference in a given parallel.

In considering inductive interference it is evidently the frequency, rather than the order of a harmonic which is important, and a component of a given frequency and magnitude is of equal importance in a 60-cycle, in a 25-cycle alternator and in a direct-current machine.

At the Deer Park convention of the Institute there were presented the results* of some preliminary work, done for the Joint Committee on Inductive Interference of California, in determining approximately the relative amount of interfering effect of given amounts of currents of different frequencies in a telephone receiver. These results are reproduced in curve *C* of Fig. 2. The amount of current produced in the telephone circuit by one volt or one ampere in the power circuit is approximately proportional to the frequency, and is represented by curve *A* in Fig. 2. Assuming the telephone terminal apparatus to be such that the same proportion of currents of all frequencies pass from the line into the telephone receiver, the relative interfering effect of one volt or one ampere of different frequencies in power circuit can be represented by curve *D* in Fig. 2, in which each ordinate is the product of the corresponding ordinates of curve *A* and curve *C*.

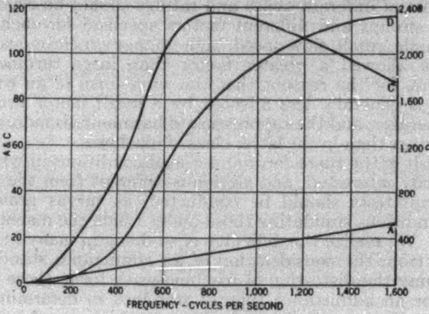

FIG. 2

The work which has been done to date indicates that the interfering effect of a compound wave shape can be represented as the square root of the sum of the squares of the effects of the sine components of the wave. An interference coefficient of an alternating current-wave can be defined as proportional to

$$K = \sqrt{\Sigma (V_f\, D_f)^2}$$

where V_f is the voltage component of the wave of frequency f, and D_f is the ordinate of curve *D* corresponding to that frequency.

By arranging a measuring instrument in a network so that the readings of the instrument will be proportional to *K* a very simple method is made available for determining approximately the interference coefficient of a wave, thus avoiding a complicated oscillographic analysis. The arrangement, beside having a transfer admittance at different frequencies proportional to the ordinates of curve *D* must have a high impedance at commercial frequencies if it is to be used with ordinary potential transformers, must give a measurable current through the branch containing the measuring instrument, and must make allowance for the impedance of the instrument, which must measure the effective value of the current flowing through it, independent of frequency.

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*See TRANS. 1915, Vol. XXXIV, page 1180.

An experimental arrangement, worked out by Mr. H. W. Hitchcock, which approximately meets these requirements

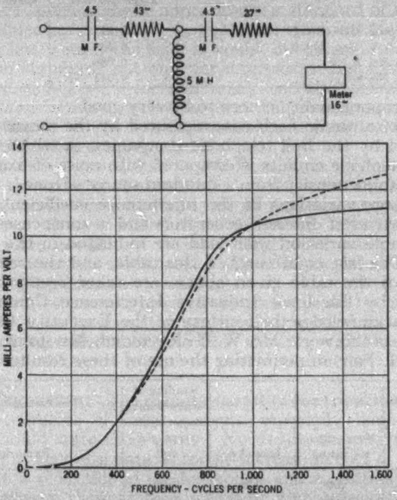

FIG. 3—CALIBRATION OF VOLTAGE WAVE-SHAPE METER

Dotted line: Curve D of Fig. 1 Full line: Curve obtained with apparatus

is shown diagrammatically in Fig. 3, which also shows the degree of approximation obtained. The particular form of network here shown makes use of a suggestion made by Mr. Chubb for a possible wave-shape standard. The measuring instrument comprises a thermocouple connected to a d-c. milliammeter. The instrument is provided with a universal shunt for the protection of the thermocouple against excessive currents. The apparatus is provided with a switch by means of which the meter can be connected across the line through a 10,000-ohm resistance so as to measure the effective voltage at the terminals. In most practical cases this is near enough to the value of the fundamental voltage so that it can be used as the fundmental without excessive error.

The few results which have so far been obtained with this apparatus are very encouraging. In the following table are given two comparisons between the noise induced in the telephone circuits in a given parallel when the paralleling power circuit was supplied from different generators and the readings of the wave-shape meter on the generators.

	Reading of wave-shape meter, milli-amps. per volt	Noise units in telephone circuits
Southhampton, Gen. No. 1	0.31	170
" Gen. No. 3	0.58	350
Iowa Gen. No. 7	0.086	1700
" Gen. No. 8	0.043	800

The proportionality is seen to be very good.

The noise was in each case measured by the means regularly employed by the Bell telephone companies, in which the noise in the telephone circuits is compared with noise of fixed quality and variable intensity from a standard source of tone.

The large variations in the interference coefficients of the voltage waves of different generators and in some cases the very considerable variation with load are indicated in the following table. The last eight cases of this table, and the second comparison of the table given above, are taken from the results obtained by the Iowa Inductive Interference Committee. I wish to acknowledge the courtesy of the Executive Committee in charge of this work, Mr. W. G. Raymond, Mr. John Drabelle, Mr. R. H. Fair, in permitting the use of these results.

Number of phases	Kv-a. capacity rating	Load kw.	Reading of wave-shape meter, milli-amps. per volt	Remarks
3	200	150	0.30	
3	300	145	0.59	
3	300	350	0.24	Same machine as above
Quarter	250	50	0.070	
Quarter	250	100	0.12	Same machine as above
2	100	50	0.70	
3	150	45	0.037	
2	50	0	0.058	
3	50	0	0.52	
3	300	100	0.086	
3	200	120	0.043	

These few results warrant the expectation that an arrangement similar to this will in the future give very valuable results in the study of inductive interference.

In establishing a standard of wave shape the inductive effects in telephone circuits are, of course, only one of several factors which must be taken into consideration. Such factors as the effect of harmonics on the operation of power circuits, and the difficulty in attaining a desired degree of reduction in the magnitude of voltages of any given frequency should be included. Weighting the harmonics proportional to their frequency has the advantage of simplicity, and excessive weighting of very high frequencies could be avoided by having a constant weighting for all frequencies above two or three thousand cycles. The *R*, *L*, *C* standard described by Prof. Bedell, with the condenser predominant at fundamental frequencies with resistance equal to the condenser reactance at resonance and with a high resonant point can be made to very closely approximate a standard of this sort for the frequencies commonly generated in electrical machinery.

To completely cover the field, it would, of course, be necessary to establish standards not only for alternators, but for motors, also, for d-c. as well as for a-c. machinery, and also for converters, rectifiers, transformers, and other electrical machinery. It is to be hoped that it will be found practicable in time to cover the whole of this rather extensive field.

L. F. Curtis: I would like to ask Prof. Bedell if, in order to determine the order of the harmonic, as well as its amplitude, in testing an e.m.f. wave, it would not be practical and desirable to make use of as a standard, a resistance, inductance and capacity, with, possibly, a variable inductance, calibrating the unit to give a certain amplitude or allowable amplitude of wave with varying positions of the inductance. It seems to me that this standard, or, rather, piece of apparatus could be calibrated with a sine wave to show the amplitude produced for different positions of the inductance, and then showing with the wave in question the additional humps or peaks induced by the higher harmonics.

C. E. Magnusson: The manufacturers of electrical machinery, and the operators of large systems, especially large central stations should state their views. No doubt, the manufacturer could give us accurate data as to the increase in cost of the generators for a reduction in the harmonics and an estimate of the relation between these factors, would be highly desirable. The operators do not, so far as I have been able to determine, appreciate quite as fully as the telephone people how much would be gained if the harmonics could be largely eliminated. I think it would be an interesting study to determine, for example, how much energy is lost in induction motors by the presence of harmonics, as only the wave of fundamental frequency produces torque. All the harmonics produce heat, but no torque. With the tremendous increase in the size of power systems and especially where a large number of central stations are combined together, it is of increasing importance that the wave forms from the several machines and throughout the system, should be as nearly of the sine-wave shape as possible.

L. W. Chubb: At the meeting last year at Deer Park, the discussion by the Committee on Inductive Interference and by

Mr. Osborne, showed that the low and very high-frequency components of voltage wave shapes are of no consequence in telephone interference, and that the great restrictions should be in the range from 700 to 1500 cycles. The operator and designer must watch the lower distortional frequencies, and others in the electrical industry are interested in the high harmonic components. The restrictions which the telephone interests wish to impose are the most severe, because the range of objectional frequencies falls within the range of the tooth harmonics in the usual commercial machines.

The setting of limits on wave distortion of generators affects the operating interests, the manufacturer of electrical apparatus and the telegraph and telephone interests. To the operator, the elimination of the low-frequency distortions is of direct importance because of the influence on losses and the paralleling characteristics. The elimination of tooth frequencies may influence the cost of right-of-way for lines in the neighborhood of telephone lines and the elimination of the very high harmonics (which seldom, if ever, come from the generators) will preclude or reduce the possibilities of oscillation and resonant breakdown trouble in the connected apparatus. The purity of the wave, which he will require, will depend upon the extra cost of machines, and the gain in cost by using the same right-of-way, etc.

To the manufacturer, the lowering of distortional harmonics is of little consequence. He must now guarantee the satisfactory paralleling of machines, and can lower the higher frequency distortions if the additional cost, which must be borne by the customer, will be justified by the savings of the latter.

The telephone interests have everything to gain and nothing to lose by close limits in wave shape, and it seems that they should bear some of the burden of the problem, by installing metallic balanced systems, which will greatly reduce the effects of inductive interference. The many discussions and schemes of measuring wave-shape distortion, and setting a standard, and the continuance of the deviation standard indicates that a just specification for wave-shape variation and its measurement is not a simple matter.

In the present paper Prof. Bedell lays greatest stress on the simple series full resonant circuit, which, after considerable discussion by the committee, seemed to be the most practical. Composite circuits have been considered, some of which give better curves than the simple circuit, but the additional complication has made it seem inadvisable to use the composite if the simple circuit will do. The simple series circuit can be made to limit any given range of frequency, but to prevent the admittance of high frequencies from falling off, and at the same time to approximate δ in the low-frequency range, it is necessary to have the resonant point at a frequency higher than that which should be penalized the most. This fault can be overcome theoretically, by the composite circuit, which will follow δ at the low frequencies, have resonance at any point in the worse range, and limit the high frequencies almost as much as the resonant frequency. The circuit shown in Fig. 4 illustrates this. It resonates at 1000 cycles per second, and limits the very high harmonics almost as much as it does the resonant frequency. This and other similar schemes are impractical, because the ordinary electromagnetic ammeters have inductance and the thermal meters are not accurate enough for the purpose. Besides, when deciding whether an admittance standard is desirable, we must decide whether the composite circuit, with more difficult testing requirements and better penalties, or the simple circuit with better testing and poorer penalty curves is the more desirable.

Generators do not have the very high harmonic frequencies, and for this reason, (since the standard is primarily for the acceptance of machines), it will not matter whether the curve turns up at high frequency, as shown in Figs. 3 and 4 of the paper. If the curve is allowed to turn up, the simple circuit with resonance at about 1000 cycles seems to me to be the best, if suitable limits can be agreed upon.

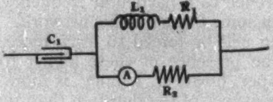

FIG. 4

A = Ammeter $C_1 = 5 \times 10^{-6}$ farad $L_1 = 0.02$ henry
$R_1 = 50$ ohms $R_2 = 83$ ohms

L. T. Merwin: The power man must recognize the fact that the subject matter of the paper is to become of exceeding importance to him, not only on account of the increasing importance of inductive interference problems that are constantly arising, but from the fact that our power systems are constantly becoming more complex, and he will be face to face with some of the problems involved in this paper.

In operating his system, however, he will not be so much interested in the form factor, as outlined in the paper, as he will in its effects on some composite circuit or branch circuit with reference to some particular harmonic that may be present in his system. This will come from the fact that as the distributing or transmission system becomes more and more complex, the presence of harmonics will constantly be thrusting themselves before him. No doubt but that the power man in the past would have avoided many of the difficulties that have come up if he had harmonics arising from his generators. I have a particular instance in mind from past experience in a system in which I had operating concern and at the time, while I realized in a vague way what was happening, I was unable to diagnose my trouble in a satisfactory fashion. This system was a portion of the Nevada, California Power Co., in the mining region of Goldfield, Nevada. It so happened that whenever there was a disturbance due to a short circuit on any part of the 6600-volt distribution system involving quite an extensive network, there was one particular span in that system that always failed. I simply mention this as a matter of operating experience. It came to such a pass that whenever there was a big disturbance on this system I immediately sent one gang of linemen to the Gold Wedge claim, where this particular span was located, and usually it would be found on the ground. Probably some of the power men here have experienced the same thing. I simply diagnosed it in a general way, as owing to a resonant condition on that particular branch. The effect of some harmonic was greatly magnified.

The subject matter of Prof. Bedell's paper, however, while it covers a case of this sort, does not put it in the concrete form that would be desirable from the operator's standpoint. He is not interested so much in the numerical value of the wave form, expressing the admittance of a great range of frequencies, as in the numerical value of the admittance of a simple composite circuit with reference to a particular frequency that might produce resonance in some branch of his network.

We power men will be forced to learn more and more of the importance of the presence of these higher frequencies in our system. The paper, however, I fancy, is more designed to take care of a broader aspect of the question than that. That aspect bears upon the problems of inductive interference which are becoming more and more important as the investigations, mutual and individual, of power and telephone companies progress.

As to the penalizing of a generator on account of its wave-form. As brought out by Prof. Magnusson, that penalizing will have to take into account not merely the designs of the telephone and power interests to avoid inductive interference, but must take into account also the commercial aspect of the question. The moment we begin to penalize generators the price will begin to rise. Further, it has been hinted that the harmonics that produce troubles in inductive interference, have a fairly limited range. If the third harmonic of a 60-cycle system does not particularly interfere with communication, it would scarcely be right or wise to put a penalty on its presence. If the 5th harmonic and the 7th harmonic do not particularly interfere with the transmission of speech and if by chance they are not of much weight from the power man's standpoint, then why penalize a generator on account of their presence. The power man can avoid difficulties in his distribution system arising from the presence of any of these harmonics, by a simple change of circuits. The introduction of inductance for instance, in any particular branch that is resonant to some particular frequency, will immediately avoid difficulties that might arise. So it would seem to me that a simple or composite circuit that would by one measurement give a form standard or a form value, should be of such a nature, if possible, that it will not involve the frequencies that are of no concern. Ultimately it will be up, probably, to the telephone companies to definitely state what numerical value should be assigned to the various harmonics in order that the manufacturer may know what to avoid. My own, very superficial, investigation in the matter seems to indicate that in a 60-cycle system the 3rd, 5th, 7th and 9th harmonics are the distressing ones in general. Now it might be that in some systems the higher harmonics up as high as the 21st say, are the ones that give the most trouble. I will admit that the means of investigation at my command are very crude but in the system with which I am connected I do not find the upper harmonics within the range of speech, present in any disagreeable degree. I do find, however, that the third is decidedly present; the 5th, 7th and 9th can be readily heard and do interfere unless quenched out in some way. As I have already said, it will be definitely up to the telephone interests to state or put a numerical value upon that range of frequencies that bothers them most. Then it will be up to the investigator and the manufacturer to try to confine his attention to this particular range.

L. J. Corbett: I want to call attention to the possible effect of a long transmission line upon the wave form which may start at the power house very true to a sine wave. At the University of Idaho we are located on the end of a transmission line about 90 miles in length. During the past year we have taken the wave form as it comes to us in our laboratory. I will not guarantee the results because the wave form was taken by an oscillograph by tracing on the screen, and was analyzed by the twelve ordinate method. We found unobjectionable the 3rd harmonic, the 5th and 7th were very slight, almost negligible, but the 9th harmonic, was of far greater amplitude than the 3rd. Now the inductance and capacity of that line, it would seem to me would alter the wave form in the various parts of the circuit, and I would like to hear from some of the men who are interested in the operation of our long transmission lines as to whether they have analyzed the curves at the various points of their lines—at the power house and also at the various terminals or service points. Mr. Merwin has touched upon one matter which I have had in mind—that it may be possible in a great many cases to correct for some of these higher harmonics by quenching them out by means of inductance, just as we do in connection with lightning arresters. We can probably put in inductances which will not materially alter the regulation of our line but which will limit the harmonics to values which are not objectionable.

And in regard to the high-frequency harmonics—I think that the present means at our disposal, that of taking the curve form of an alternator and analyzing it, is about the only method that we can use at the present time. Of course, the relative harmonic of a 25-cycle generator which will cause trouble in a telephone circuit will differ from the relative harmonic of the 60-cycle generator which has the same frequency, and as has been pointed out, those frequencies within the speaking range are the only ones which will cause trouble with voice currents. Those are the ones which should be eliminated. With the apparatus which is already at hand in the various power stations it seems to me that the only possible method of correction is by some such method as indicated, that of quenching out the objectionable harmonics.

J. B. Fisken: Mr. Corbett has expressed a desire to hear from the operating men as to what investigations they have made on this question. As one operating man, I would tell Mr. Corbett that I have made none. We operating men, I think, all agree that we have harmonics. I think we all agree that, like the poor, the harmonics will always be with us. If we could get rid of them, we would be very glad to do so. The question of the elimination of harmonics, to my mind, is purely a commercial one. If the public will submit to paying such rates for service that we can buy more expensive machines, then, undoubtedly, the manufacturer can give us those machines. But, in the last analysis, it is purely a commercial proposition. I thoroughly believe that, for any reasonable expense we should endeavor to eliminate the harmonics, but beyond that we can not go, and the burden will be placed upon the telephone engineers of finding some means of carrying on their business with those higher harmonics running around loose. There is another feature of the case that occurs to me. We might have an alternator designed that would be entirely free from harmonics. We might have a line designed that would be entirely free from harmonics, but when the time comes that we have to change, possibly, our scheme connections (and in an interconnected network that is always possible), then is it not a fact that our former computations are practically of no value? In other words, instead of operating a particular generator on a particular line, we may have to operate that generator on a different line.

W. D. Peaslee: Unquestionably, if we can get a dollar per kilowatt for energy for lighting purposes, we can generate electricity that has a sine-wave voltage with practically no harmonics, and we can give the telephone people lines with which they can talk from one end of the continent to the other, and go their way in peace. But it can not be done at the present rates, under the existing conditions. It is very pleasing to see the difference in the whole situation in the inductive interference problem a year ago and today. The situation today shows that cooperation is starting. At the present time, the telephone people, I think largely because of the eternal dollar, have "passed the buck" entirely to the power people. They make the sweeping statement that all harmonics are very bad, and that they should be penalized in proportion to their frequency, and, therefore, a million-cycle wave should be reduced to absolute zero, putting the proposition flatly up to the power people in a way that is impossible of commercial solution. I personally know that it is possible to take a telephone line suffering from inductive interference, and by proper tuning methods, damp out one at a time the 3rd, 5th, 7th and 9th harmonics. I know that you can take a telephone line and damp out these harmonics for a distance of 70 miles, and do it successfully. The telephone people assure us that these methods are not efficient, and that it can not be done successfully. That is not true. I know it is possible to take a weak telephone current, and, by means of the audion amplifier, step it up to considerable proportions. I am firmly convinced that one of the solutions of this problem will be wiping out these harmonics below the frequency of the voice currents, and if in doing so, the attenuation of the voice currents is very great; I see no reason why the audion amplifier will not step up the pure wave, attenuated as it is, and pass it on again. That is a point on which the telephone interests are not giving us as much information as they should. There is no question that their laboratories are working on this matter, and that they have a great deal of valuable information, but it is like pulling teeth from a cross cut saw to get any information from them.

The only possible solution of this problem is for the power companies and the manufacturers, and the telephone people to get together, and, to use a common expression, lay their cards on the table. In that way we can get the best solution possible, and I look forward to the day when this will occur, because of the immense improvement in the situation at present over a year ago.

Harris J. Ryan: There must be a standard of wave-form. We have long since found such to be the case. In the standardization rules of our Institute, it seems to me, as I recollect now, from the beginning virtually, there has been a standard of wave-form but, as pointed out in the paper it is not satisfactory for the easons there given.

It seems to me well to take into account a few of the very broad elements in the matter. The telephone interest is endeavoring in a very strong effort to transmit fundamentals and harmonics and to transmit them faithfully. On the other hand, the power interest would gladly supply electric energy in fundamental form only, and discard the harmonics. Any extension or amendment of our present definition of wave-form should be undertaken with great care because of the important, deeply rooted, widely ramifying factors.

R. W. Mastick: In regard to Mr. Peaslee's remarks concerning the use of drainage devices applied to telephone circuits for the purpose of filtering off the disturbing frequencies and the use therewith of amplifying devices to again restore the magnitude of the voice currents; Dr. Bedell has correctly said that it is vitally important in a telephone circuit to transmit various frequencies in their relative proportions, which are within the range of the disturbing frequencies, in order that undistorted speech may result. This statement in itself answers Mr. Peaslee's suggestion, for if drainage devices are used, certain currents of voice frequency which are identical with the disturbing frequencies will also be drained off. Therefore, even though an amplifying device be used, it is obvious that the relative proportion of frequencies in the voice current will not be the same, hence distorted speech will result. Again, consideration must be given, even though such a scheme were feasible, to the number and complexity of telephone circuits in use, to which it would be necessary to apply such a device.

L. T. Merwin: Mr. Mastick's reference was to some very crude experiments that I had been carrying on with our own telephone line, which is on the same supports as our 66,000-volt conductors for a distance of approximately 70 miles. These experiments consisted of the shunting out of the lower harmonics that were particularly distressing; so much so, in fact, that it made the use of our own telephone system for dispatching, extremely inadequate. As a matter of fact it was almost non-usable until we had devised, after much stumbling, composite forms of shunts that would effectively shunt out the 3rd, 5th and 7th harmonics, and the 9th if it were so desired. It was remarked that I did not find any harmonics above the 9th that interfered in any way with satisfactory communication, and that while talking with a particular operator of Swedish nationality it was observed that the intelligibility of his speech was remarkably increased. Now that is an actual fact, and it can be attested to by Mr. Peaslee and I think by Mr. Condit, the attention of both of whom I called to this peculiar phenomenon. I am not in a position to say how my own voice sounds over this line.

I would like to emphasize a point brought out by Mr. Peaslee, that it will assist in the solution of this problem very materially if the telephone company freely divulge the results of their own experiments as we discuss these problems with them.

Just a moment more on the penalizing of generators. If transposition is effective when a power system is balanced both for transverse and longitudinal induction, and if the parallelism is a simple one, and by the means of these transpositions the harmonics can be quenched out at very little cost, why should it be necessary to penalize a generator if it produces these harmonics? It reduces again to purely a commercial problem.

It may be cheaper in some instances to take the standard form of generators as we now have them and by a small expenditure entirely eliminate the troubles arising from inductive interference through transposition or other means.

Frederick Bedell: We are not in a position at present to adopt a final exact specification for a standard of wave-form, but with the material that is before us and with further study, certainly progress should be made. It seems that all are agreed that several of the admittance standards discussed today are superior to the present deviation standard. Now, whatever standard is adopted, it will probably not have its numerical values specified in the first instance so as to hold for all time. With experience we will no doubt later have to modify the specification of the standard; the best we can do at present is to make a first approximation, agreed to by all as better than the present standard, and later improve it. I believe that a simple standard can be found that will meet the need for practical purposes. The simple standard has the advantage not only of practicability but from the psychological standpoint it is more desirable than a composite one. We know then what we have got, for by experience we are all familiar with the characteristics of a simple circuit. Even for those of you who are most accustomed to calculations with involved circuits there is something in a composite circuit which makes it indeed difficult, if not impossible, to comprehend its characteristics at a glance. Even if ultimately a composite standard were to be the more desirable, I believe it would be unfortunate to adopt it in the first instance and to try to swallow it all at once. How much better it would be to put forth a simple standard which all can understand, and then later modify it by shunts or what not, should we so desire. We will have had the idea of a volt-ampere standard and a modification of that idea can then be readily accepted. But I believe that the simple standard can sufficiently meet the situation and that we should not try to get a law penalizing the harmonics, supposedly, with theoretical exactness down to the last dot. Such theoretical exactness would be difficult to attain for the reasons pointed out here today to the effect that wave form varies in different parts of a system, and futhermore to the effect that wave form at the same point of a system varies from time to time with load conditions. Now these variations due to circuit and load conditions, which vary with time and space, are not properly to be charged up to the generator. We want to get at a pretty fair approximation of the penalty to put on the generator, but we cannot charge it with all the idiosyncrasies of the line. Some of those who have been working on this subject have seemingly thought that there was some ultimate exact law which we could get at which would prescribe the precise penalty for this or that harmonic, and that we should make every effort to ascertain this with precision, and should then adopt a standard which would fit it, not approximately but exactly. I believe in accuracy so far as it is possible, but in this case if we can get the general trend of the relationship between frequency of harmonics and their deleterious effects and get a corresponding standard that is easy for us all to use and to understand and to apply, I think we will have done all we can do, at least for the present, and possibly the results will stand for a long time. As several of the speakers have pointed out, it is a matter involving the power operator, the telephone operator and the manufacturer; their several points of view should be harmonized, weighed and balanced and, if possible, a result obtained that meets the views of all of the people concerned so far as possible. It has also been pointed out by several of the speakers that it is an economic or commercial question, and that is true. By paying more and more money you can obtain better and better apparatus, and better and better service, and there again it is a question of weighing and balancing the importance of cost versus service. Mr. Curtis asked a question as to whether wave analysis could not be made by an *R*, *L*, *C* circuit by varying the inductance so as to show the amplitude of particular harmonics. This method of analysis has been carried out and a reference on the subject has been given in the paper. The method has been used, I believe, in recent investigations by the Joint Committee on Inductive Interference, and I believe has also been used in the laboratory of manufacturing companies in the study of this problem. Mr. Merwin suggested that the telephone people should state definitely the numerical values that would be permissible for various harmonics. This can hardly be done. If you cut a particular harmonic to, say, half its value, it will improve the service; if you cut it to say, one-fourth its value it will improve the service still more, and so on; so it seems no matter how good, within practical limits, you can get the wave form, the telephone service would still be improved by further improvement in the wave form. In other words, it would be desirable to reduce the harmonic from the telephone standpoint even beyond the practical limit. It does not seem, therefore, that we can get at that in just that way. We can get a standard which approximately gives the proper law of penalizing; we should make it not too hard at first so it wont be an undue hardship on any one; then, with the general scheme standardized, the numerical values of the standard can be adjusted little by little, so as to put on the screws gradually from year to year, so that they will not pinch too much and yet will bring the pressure where it seems desirable. It will be understood that, in the paper and in the discussion by the author and by other persons on the subcommittee that have been dealing with the subject, neither the Standardization Committee nor the Sub-committee is committed in any way. It was the purpose to have this open discussion so as to bring out the facts.

Presented at the Pacific Coast Convention of the American Institute of Electrical Engineers, Seattle, Wash., September 8, 1916

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INSULATOR FAILURES UNDER TRANSIENT VOLTAGES

BY W. D. PEASLEE

ABSTRACT OF PAPER

The operation of a high-voltage transmission line involves changes in energy distribution that are very conducive to high-frequency disturbances and transients of very steep front. These are often superposed on the normal frequency voltage of the line in such a way as to impose great stresses on the insulators.

The mechanism of failure of an insulator is of great importance to those designing and operating transmission lines. This paper presents the results of recent investigations on the failure of insulators under impact and combined impact and normal-frequency voltages. Microphotographs of the resulting failures are included.

The breakdown of a dielectric involves energy which is a time function and the importance of the duration of the stress in determining the magnitude of the voltage necessary to puncture an insulator is discussed.

Due to the short duration of transients, insulators are often punctured repeatedly by them, the procelain in the puncture solidifying again on account of the small energy involved. These sealed punctures however weaken the insulator, lowering its dielectric strength materially.

The importance of the elimination of air holes and defects in the porcelain is shown.

Some essential features of a successful line insulator are stated.

INTRODUCTION

A PARTICULAR dielectric will be ruptured or broken down when the dielectric flux density exceeds a certain value and this flux concentration lasts for a finite time. It is necessary that the time of application of the stress be finite, as any breaking down of a dielectric involves energy which is a time function. This has been well shown by the experiments of Peek*, and others in the study of corona formation, and it has been shown that, under transient voltages, the shorter the time of application of the stress the greater the voltage necessary to produce break down of the dielectric.

Thus the breaking down of porcelain used in the manufacture of high-voltage insulators demands the application of the stress for a period of time great enough to permit the accumulation of sufficient energy to destroy enough of the porcelain to puncture the insulator, and the shorter the time of application of the voltage the greater will be the necessary voltage to produce break down.

In a study of insulator failures it will, then, be essential not only to consider the voltage applied to the insulator but also the duration of the voltage. If a transient voltage of very short duration measured in micro-seconds be applied to a dielectric, such as porcelain, of sufficient value to rupture it, with very little power behind it we might expect to find the porcelain punctured, but since the time of the transient is very short the energy involved is small and therefor the destructive effect very local. Thus we might expect to find the porcelain melted over a very small path and solidifying again immediately upon the removal of the transient leaving the insulator in nearly as good condition as it was before the application of the puncturing voltage. However, due to the short duration of the transient voltage and the instant solidifying of the porcelain some impurities would be carried into the porcelain and sealed there, thus weakening, to a certain extent, the dielectric strength of the insulator.

If, however, simultaneously with the application of this transient we should apply a 60-cycle voltage of sufficient value to follow the path which the transient voltage had broken through the insulator, and with sufficient power behind it to keep this path in a molten condition the power arc would be maintained through this path and the insulator destroyed.

Whenever a steady condition of a circuit containing inductance and capacitance is disturbed there is set up an oscillatory transfer of energy from the electromagnetic to the electrostatic fields, or vice versa with a concommittant change in voltage or current conditions or both. The character of the change is dependent upon the relation between the resistance, inductance and capacitance in a manner familiar to all electrical engineers. In a high-voltage transmission line we have the distributed inductance and capacitance of the line and lumped inductance (transformers), and lumped capacitance, (lightning arresters and high-tension transformer windings). These form a circuit that is highly susceptible to oscillations and responds very readily to disturbance of the steady condition. Thus an arcing ground may cause large, relatively low-frequency surges and trains of high-frequency waves, the damping of which depends on the resistance of the oscillatory circuit. The frequency of the oscillations in this case will depend on the inductance and capacitance of the oscillating circuit, so on the location of the arcing ground. Thus it will be seen that an arcing ground may produce oscillations of widely varying frequency and varying in damping from well sustained wave trains to abrupt front transient impulses. In the same way a "spill over" of an insulator or the charging of a lightning arrester may subject a line to oscillations of voltage or current or both. The operation of switches especially of the air-break type is also often productive of vicious transients.

Since then a great many of the phenomena attendant upon the operation of a modern transmission line involve the superposition upon the sixty-cycle voltage of transients or highly damped high-frequency wave trains, a knowledge of the effects of these transients on the insulators of the line is of great importance and the investigation upon which this paper is based was undertaken to discover if possible the effect of these transients, and from these effects to determine advisable precautions in the manufacture and use of high-voltage insulators.

It has been shown by Ryan*, that the effect of the superposition of a radio-frequency sustained wave train on an audio-frequency wave is to give the combination a striking distance in air equal to the sum of the sparking distances of the two separately. If then we superpose transient voltages upon a normal-frequency wave the stress imposed by the combination will vary between the limits represented by the sum of the maximum transient and maximum 60-cycle voltages and their difference, according to the part of the cycle of the normal frequency wave in which the transient occurs, being the sum if a positive transient coincides with the positive maximum of the sixty cycle wave and the difference if it coincides with the maximum of the negative half wave. At any other point of coincidence the effect would be somewhere between these two limits.

The probability that a transient of known duration will fall within a certain part of a 60-cycle wave if impressed at random on the wave can readily be shown mathematically. Using the part of the positive half of a 60-cycle wave above the effective value it is found that one out of every fifteen million random impulses each consisting of the positive half of a 750,000-cycle wave will be likely to fall within this interval. If, when this does occur, the summation of the two voltages is sufficient in amount and duration to puncture the insulator the power arc would be very likely to follow the transient, blowing out the melted porcelain before it could solidify, thus permanently puncturing the insulator. It will be readily appreciated however that a transmission line might be operated for several years without this coincidence occurring and further that it might occur very locally and so effect only a few or even single insulators.

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*Sustained Radio-Frequency High-Voltage Discharges, Trans. Inst. Radio Engineers, Sept., 1915.

METHOD

An insulator of the type shown in Fig. 1 was selected because of the zone of the flux concentration in the plane at section *AB* and because the dielectric flux concentration near the pin in the inner petticoat was about seven times that near the cap in the outer petticoat. For the purpose of the test the cement can be considered as a perfect conductor and the manufacturers claimed a specific inductive capacity of 4.8 for this porcelain. Knowing these constants the dielectric field can be drawn to scale and the direction of the lines of force determined as indicated roughly in the figure. This insulator, designated as No. 1, and another of somewhat similar design (No. 2) and a 66,000-volt triple-petticoat pin insulator (No. 3) were subjected to a combination of a 60-cycle 50-kv. wave with a transient highly damped and corresponding to one half of a 750,000-cycle wave with a maximum of 30 kv. this transient applied at random with respect to position of coincidence with the 60-cycle wave.

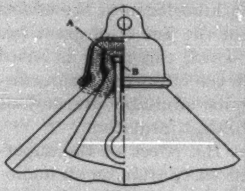
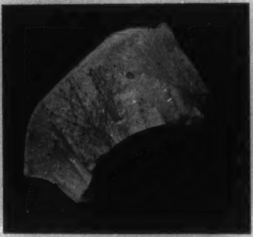


FIG. 1—TYPE OF INSULATOR USED IN TESTS

After approximately eight million impulses insulators Nos. 1 and 3 broke down. Insulator No. 2 was then removed but punctured under the attempt to apply dry flash-over voltage, (95,000 volts).

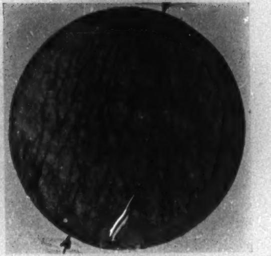
DISCUSSION OF DATA

Insulator No. 1 was then carefully broken up and examined. The zone *A B* was riddled with fine hair-like lines which under the microscope proved to be tubes of slightly discolored melted porcelain. The discoloration seemed to be due to impurities



[PEASLEE]

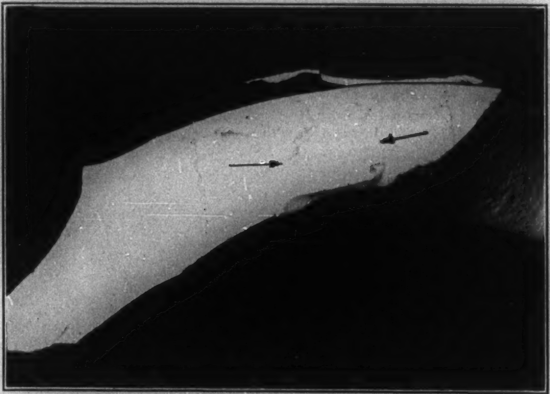
FIG. 2—FRACTURES FROM ZONE A-B INSULATOR NO. 1. TWO AND ONE-HALF DIAMETERS — INNER PETTICOAT



[PEASLEE]

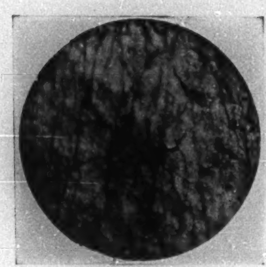
FIG. 4—TEN DIAMETERS

Vol. 35
1916

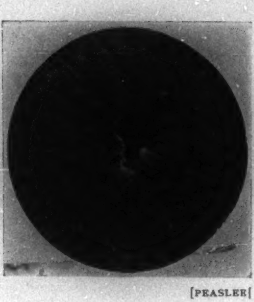


[PEASLEE]

FIG. 3—POWER ARC PUNCTURES OUTER PETTICOAT INSULATOR NO. 1—TWO AND ONE-HALF DIAMETERS

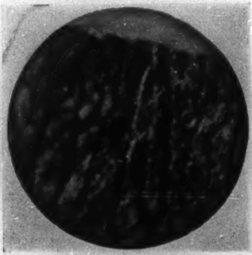


[PEASLEE]
FIG. 5—TEN DIAMETERS

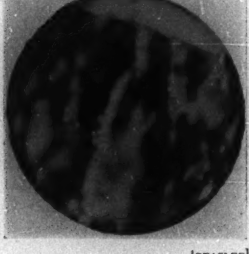


[PEASLEE[
FIG. 6—TEN DIAMETERS

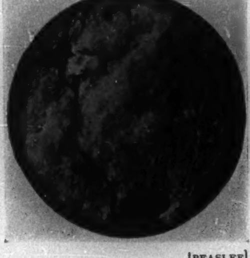
[PEASLEE]
FIG. 7—TEN DIAMETERS



[PEASLEE]
FIG. 8—TWENTY DIAMETERS



[PEASLEE]
FIG 9—FORTY DIAMETERS



[PEASLEE]
FIG. 10—TEN DIAMETERS

carried into the porcelain by the puncturing arc and sealed into the tube of melted silica. The appearance of this puncture was very different from that caused by the power arc as shown in Fig. 3, and it is very significant that while these fine punctures were very numerous in the zone *A B* in the inner petticoat, there were practically none in the outer petticoat, and what few were found were not appreciably discolored. Also the inner petticoat fractured in what might almost be called a cleavage plane along this zone of flux and puncture concentration, showing that the porcelain had been weakened mechanically as well as electrically by these break downs even though they had sealed up in time to prevent the formation of a power arc.

Fig. 2 shows a surface fractured from zone *A B* magnified two and one-half diameters showing the fine cross lines, each a tube of melted silica, representing a puncture by a transient that has sealed up preventing the formation of a power arc. This sample is taken from the inner petticoat.

Fig. 3 is from a photograph of the outer petticoat of this insulator magnified two and one-half diameters showing the two power punctures that occurred in it when the inner petticoat, weakened by these impacts, finally ruptured. This photograph shows very clearly the marked difference between the puncture produced by a transient voltage only and one followed by a power arc.

Microscopic studies of these samples were extremely valuable and reveal many interesting features that the pictures cannot show regarding the mechanism of the break down etc.

Referring to the micro-photographs, Fig. 4 is taken from the inner petticoat in zone *A B* of insulator No. 1 showing the radiating punctures from the edge of the specimen nearest the pin. The broad white streak between the arrow points is the path of the power arc that finally, striking through this weakened zone, punctured and destroyed the insulator.

Fig. 5 shows a portion of the same specimen taken along the path of the power arc further towards the outside of the inner petticoat. The tendency of the transient voltages to jump across between defects in the dielectric is very noticeable here, and Fig. 6, taken from insulator No. 1, shows this very well, as seven distinct and separate punctures may be seen striking through this air hole. As this is magnified ten diameters the size of the defect can be appreciated and also the care necessary in the manufacture of the porcelain to produce a product free from defects that will weaken the insulator.

Figs. 7, 8, and 9 are taken from the same specimen from insulator No. 2 but magnified to different diameters as indicated.

Fig. 10 is taken from insulator No. 3, and shows very well the tendency of the transient to seek out and follow a series of defects in the porcelain. Fig. 11 is also taken from insulator No. 3.

Fig. 12 is taken from the inner petticoat of insulator No. 2 and shows very clearly the path of the power arc as well as the paths of the transients.

FURTHER INVESTIGATIONS

It would seem from a consideration of the fundamental mechanism of dielectric break down that two things must be avoided to prevent damage to an insulator; a concentration of dielectric flux above a certain value and a finite duration of this concentration. This seems well borne out by the data secured, as the failures shown in the photographs occurred in the zone indicated by this theory, and as was expected, were almost entirely confined to the inner petticoat of each insulator. As a further investigation a piece of grooved porcelain was secured and a conductor placed in this groove with a plate against the other side of the porcelain opposite the groove. The resulting flux distribution is roughly indicated in Fig. 13. However it was feared that the corona forming on this conductor would act as a relief valve for the impact of the transient, the dielectrically weaker air absorbing the shock and so protecting the porcelain. Therefor a second sample was prepared as shown in Fig. 14 and the conductor covered with paraffin, the covering extending well up on the connection to the conductor to the point where the separation of the plate and conductor would prevent the formation of corona, thus forcing the impact onto the porcelain.

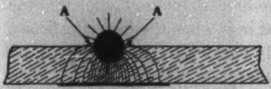


FIG. 13

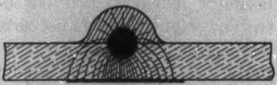
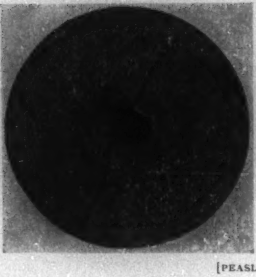


FIG. 14

A third sample was prepared with a needle placed with its point against one side of a piece of porcelain, the whole needle being imbedded in sealing wax, while a plate was placed on the other side of the test piece.

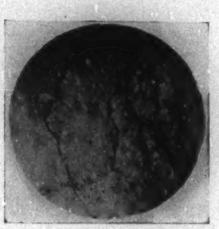


[PEASLEE]

FIG. 11—TEN DIAMETERS

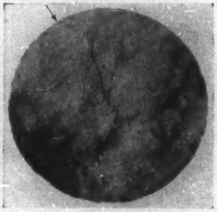
[PEASLEE]

FIG. 12—TEN DIAMETERS



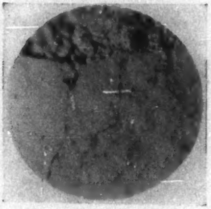
[PEASLEE]

FIG. 15—FIVE DIAMETERS



[PEASLEE]

FIG. 16—FIVE DIAMETERS



[PEASLEE]

FIG. 17—FIVE DIAMETERS

Vo
19

These samples were subjected to the impact tests previously described, except that in this test the transients corresponded to a half of a 460,000-cycle wave, for about 70 hours with approximately 120 impacts per second. At the end of that period the samples shown in Figs. 13 and 14 were broken along the bottom of the grooves and the other under the needle point.

The sample arranged as in Fig. 13 showed no traces of puncture, while the one shown in Fig. 14 was liberally sprinkled along the bottom of the groove with the characteristic transient puncture. In none of these test pieces did the power arc follow through as the 60-cycle voltage was purposely kept low.

Fig. 15 shows the puncture found in the bottom of the groove in test piece shown in Fig. 14, and Fig. 16 shows the puncture found under the needle point. It should be noted that in this specimen the thickness of porcelain between the needle point and plate was twice that between the conductor and plate in Figs. 13 and 14.

Fig. 17 is included as of interest in showing the manner in which the transients strike into the porcelain from irregularities in the surface of the porcelain or cavities in the cement.

CONCLUSION

From what is now known of the action of high voltages of normal and high-frequency sustained waves and of transient duration, it is apparent that the successful insulator for continued service in high-voltage transmission lines must be designed with the following points in mind.

1. The actual puncture voltage of the insulator divided by the safety factor desired must be above the sum of the normal frequency maximum voltage that will be encountered in operation, (taking due account of relatively low-frequency surges), and the maximum transient or sustained high-frequency voltage that may be impressed on the line. If this is not done the insulator will in time be weakened by the impact of these transient voltages and ultimately must fail.

2. Points or zones of excessive flux concentration must be avoided. A careful porportioning must be undertaken to avoid the extreme dielectric field distortion and concentration commonly met with in insulators now on the market. Ratios of flux density in different parts of the field of eleven to one have been noted in certain insulators and these have almost universally given trouble in time on high-voltage lines.

3. The porcelain must be free from air bubbles and defects

and this is a problem that must be met by the ceramic engineer before it is possible to manufacture reliable insulators.

4. The insulators should have a puncture voltage as many times the dry flash-over voltage as the desired safety factor. The importance of this point is not always realized but when it is remembered that there is a large time lag in the break down of air it will be realized that severe impact stresses can be placed on an insulator by transients. With a sufficiently abrupt transient, a voltage of much more than flash-over may be impressed on an insulator in air and this is in the form of an impact delivered inside the insulator, weakening it at every application.

5. To avoid placing dielectrics of different dielectric constants in series, the surface of the insulator should follow, in so far as possible, the lines of force of the dielectric field.

6. Caps and metal parts should be smooth and of large radii of curvature to make the corona forming voltage as high as possible. It is possible to design an insulator that will flash over after the manner of sphere-gap break down without the formation of corona.

7. The design should be such mechanically as to keep the lines or zones of mechanical stress removed from the lines of electrical stress, and where this is impossible the two stresses should be as nearly as possible at right angles. This point has been brought out by recent study of the influence of the line of action of mechanical stress in porcelain upon the path of the resulting fracture.

These investigations were carried out in the high-tension laboratory of Oregon Agricultural College and the writer takes this opportunity to express his appreciation of the assistance of Mr. C. E. Oakes and Mr. Winfield Eckley who aided him in the test, and Prof. S. H. Graf of the Department of Experimental Engineering by whose courtesy the micro-photographs were made possible. Grateful acknowledgment is also made to Mr. L. T. Merwin for his very valuable suggestions in constructive criticism of the manuscript.

It is not felt that the data here presented bring out any previously unknown phenomena as this action has long been suspected by or known to many of the workers in this field, but they are presented as the preliminary results of an extensive investigation now in progress on the subject and it is hoped that a study of these photographs will increase the respect of the engineers, who are designing and using insulators, for the destructive ability of transient voltages.

DISCUSSION ON "INSULATOR FAILURES UNDER TRANSIENT VOLTAGES" (PEASLEE), SEATTLE, WASH., SEPTEMBER 8, 1916.

J. B. Fisken: The author makes this statement: "The operation of switches, especially of the air-break type is also often productive of vicious transients." My experience has led me to believe that the substitution of the word "sometimes" for "often" would improve this paper very materially. We have never seen any occasions, in our system, where the operation of air-break switches was serious, and we have used them to quite a large extent. I want to ask Mr. Peaslee whether we are to believe from Fig. 1 that the potential gradient is constant through that insulator?

W. D. Peaslee: No. By no means. About 7 to 1.

J. B. Fisken: Then, there would be portions of that insulator where the flux density would be very much greater than it is in others?

W. D. Peaslee: There were. About seven to one.

J. B. Fisken: One of the most interesting things in the paper is the time element. There is something there that I, as an operating man, had never before realized. It seems that those high frequencies, which we all want to get rid of, keep working and it may be some considerable time before the insulator breaks down. I want to ask Mr. Peaslee if he does not think better results could be obtained if the top of the insulator was entirely covered with a metallic coating, and instead of having the tie wire which holds the high-tension wire, rest on porcelain, it should rest on some portion of the metallic covering? I ask that question for the reason that most of our punctures, or a large number of the punctures we find, take place from the tie wire and not from the conductor.

Robert Howes: We have heard a number of valuable comments upon the poor quality of insulators. About fifteen years ago I had a part in the construction of the first transmission line of the Washington Water Power Company to the Cour d' Alene District. It was early work in the 60,000-volt field and we were threatened with dire consequences, so all of us connected with the work exhausted our knowledge and wits to eliminate the threatened dangers. The construction in some features would be now considered obsolete, in others it is quite up to date, and some desirable modifications have been made. Still my record shows that in the first seven months of operation the line was out but a total of thirty-two minutes except by previous arrangement. Further, I understand from Mr. Fisken, who has had the handling of that line in his department ever since it was put up, that there have been almost no insulator failures from electrical causes on that line.

About eight years ago I had charge of the designing and construction of two parallel three-phase lines covering a distance of about sixty-five miles in British Columbia, the voltage was about

34,700 delivered with star connection and with neutral grounded at the power house. These lines were thrown on the power house suddenly upon completion and operated continuously. I have never heard of an insulator failure except by mechanical injury. However, my recent knowledge of the line is not sufficient to state whether any weakening has developed with age.

In both of these lines the precautions taken in designing were, grounded neutrals at the power house, lightning arresters, few in number, but located exactly at the terminals as opposed to location near the terminals. The insulators were tested to at least three times the voltage from wire to ground. In the British Columbia line as I remember it, each piece of the three-piece insulator was subjected to about 30,000 volts. In fact I think the top piece was subjected to 40,000 volts in actual tests. And the assembled parts to over ninety thousand, the test being made between salt water terminals. In these lines the intention was to be sure that the insulators had the same safety factor over working conditions that would be required in steel construction, for purposes of equal merit. It seems that we should not place more confidence in porcelain than we would in steel. Again as we figure steel beams on the stress in extreme fibers, so we should figure insulators on the stress in the most strained portions. It seems clear to me that the practical solution of the rotten-insulator question is first to keep insisting on proper safety factors over the working voltage, and second, use means to prevent excess voltage. Now in regard to the means of preventing excess voltage there is a little piece of ancient history in connection with the Washington Water Power Company that has influenced me whenever I have had anything to do with the installation of lines. Installed in that power house there were three monocycle generators. The connections were as follows: Generator, impedance coil, lightning arrester, bus bar, line. When the three units were in operation there were accordingly three lightning arresters at the power house. These machines were operated nominally at about 2300 volts. They had been operating for years without any serious difficulty, or at least for a considerable period. Under my direction, we installed a wattmeter which was connected by means of a two-circuit current transformer connected in the two outside wires of the bus bar. There were no changes made in the lightning arrester connections whatever. At the first slight lightning disturbances that could be noticed one of the generators punctured to ground. This was cleared up by the power house foreman and the lightning arresters gone over thoroughly and the other conditions remained as before. A very short time after that a second slight lightning disturbance caused a second puncture in the same place. I then went over the lightning arresters myself and carefully examined everything to make sure that nothing had been neglected. But the next slight amount of lightning caused a third puncture in the same place. I then thought it must be due to some change in conditions, and the only change that had been made was the installation of the wattmeter, so without changing anything else I took an ordinary air-gap arrester and connected it exactly at the outside terminals of the current transformers, after which the machine ran until it was put out of commission by disuse, without any further difficulty, whatever. Ever since that time I have positively insisted that the lightning arrester connections should be made at the first material impedance and exactly at the terminal of that impedance and not at some distance away. I have noticed several transmission lines where there have been lightning disturbances in which the lightning arrester connections were made at some distance—say at from fifty to two hundred feet from the first impedance—and those lines as far as I have noted were lines that had trouble from lightning. Now, I say lightning—I mean any high-frequency disturbance similar to lightning on the line—and it has been my experience such as I have had in both low and high-tension lines, that with insulators tested as above and the lightning arrester connection made exactly at the impedance terminal there has been no serious trouble from such disturbances.

L. T. Merwin: On this question of the impact of the higher transients on our insulators, I will confess that in years gone by, when an insulator failed from puncture or was destroyed from whatever cause, the man in charge of the repair dropped it on the ground at the foot of the pole where it was found and a new one was substituted. The line was again put in commission and that was all there was to it. Now, following experiments that are going on in the various laboratories of our institutions of higher learning, we are beginning to know why these things have been taking place. Very often it happens that the note of warning has been sent out and absolutely disregarded. I feel that probably we are disregarding every day things to which we should attend. We have had just exactly the information and the remedies already voiced if we would only listen to the notes of danger. After Mr. Peaslee had shown me the rough draft of this paper we had a failure on our transmission line, the results of which you have all seen in the fractured insulator which has been shown here today, and which absolutely corroborates his contention in the paper. Now, Mr. Peaslee has developed the theory born from the fruits of experimental investigation in his laboratory, equipped with apparatus that is beyond the range of the ordinary operating man to have, but here is a confirmation following immediately upon the heels of his announced results that is very gratifying.

Harris J. Ryan: This paper on insulator failures under transient voltages has given us an intimate and correct idea of the manner in which porcelain fails under electric stress. It properly emphasizes the almost instantaneous porcelain fusing ability of an undue amount of charging current and the powerful character of the mechanical blast that is generated by an electric spark in its own length. I heartily endorse most of the author's conclusions, drawn from the results of his experiments. I trust he will continue his work along present lines, and in so doing, that he will employ definitely porous and non-porous porcelain, the latter with and without absorbed moisture, so as to develop more evidence in regard to the basis for Mr. Osborne's claim of yesterday, that porous insulators are capable of reliable service. It is, of course, conceivable that water-logged porcelain may endure transient over-voltages pretty well. As evidence thereof, we have the failure of the oscillator to pick out defective insulators when porous and water filled. In regard to sustained 60-cycle voltage, the matter is quite different. Of that there can be no shadow of doubt. The great difference between wet and dry porcelain production processes is; in the former the porcelain can not have its pore systems closed by vitrification, while, in the latter, it can. No water-logged porcelain will endure between conductor electrodes an ample amount of sustained power voltage to render it reliable for high-voltage service.

R. W. Mastick: Mr. Fisken has called attention to the statement in Mr. Peaslee's paper and objected to it that "The operation of switches, especially of the air-break type, is also often productive of vicious transients". I wish to add some evidence in support of Mr. Peaslee's remark.

A few months ago, it was my privilege to conduct an investigation on an operating power system of transients produced by the operation of both oil and air-break switches. A number of observations were made and recorded by means of an oscillograph, of switching operations under both load and no-load conditions. These observations were made both at the point of switching, and with many miles of transmission line intervening between the switch and the point where the oscillograph was located.

In several instances, transients of a violent character were recorded and the presence of frequencies of a high order definitely indicated. The transients produced by oil switches were not so violent, nor as long sustained as those produced by air-break switches.

It is of interest to note that these observations of transients were all recorded by using the residual voltages and currents of the power system.

J. B. Fisken: I had two reasons for making the statement that I did: One is the practical reason that we are operating air switches without, apparently, having any difficulty. My other reason was that some years ago, we made a number of oscillograph tests with air switches and oil switches, and we could not see that there was any material difference. It is quite possible that our methods of connection were somewhat crude, and that we did not get as refined a test as Mr. Mastick would get, but I still am of the opinion, Mr. Mastick to the contrary notwithstanding, that this talk of the extreme high frequencies or disturbances caused by air switches, is not well taken.

R. M. Boykin: While I have heard but little of the discussion on this subject, I would like to ask Prof. Ryan what he considers water-logged porcelain, or water-logged insulators, and how much water by weight or volume can porcelain absorb before rendering the porcelain useless for insulator purposes.

Harris J. Ryan: I can only answer that question in part: The porous porcelain referred to just now is of good quality except that its porosity exceeds some low value, perhaps a tenth per cent by volume, just how much we do not know as yet. An insulator body that has its pores filled with water is liable to early failure. The resistivity-temperature relation for porcelain is negative and very high, besides it ceases altogether to be an insulator and becomes an electrolytic conductor at about 300 deg. cent. Thus in a water filled porous porcelain body subjected to power-voltage, the in-phase current will be concentrated upon a narrow route or core, producing intense local heat and puncture. Much trouble undoubtedly has come from the fact that dry porous porcelain has at all ordinary temperatures about the same high resistivity and dielectric strength as non-porous porcelain. It is here understood that non-porous porcelain is that, in which the pore systems are well limited and in which they do not in any single instance extend through appreciable depths of the porcelain bodies.

A. A. Miller: I would like to ask Prof. Ryan about his statement as to the effect of temperature upon the dielectric strength of the material of the insulator. Do I understand that he refers to a temperature of 425 deg. cent. as being the temperature of the material along the path of the puncture or does his statement cover general results of tests made upon masses of porcelain at known temperatures?

Harris J. Ryan: In speaking of the loss of all dielectric strength for porcelain at 300 deg. cent. I had reference to the results of C. E. Henderson and G. O. Weiner which may be found in their paper on, "Effect of Temperature on the Dielectric Strength of Porcelain Insulators," published in the Transactions of the American Ceramic Society, Vol. XIII, p. 469, 1911.

W. D. Peaslee: With reference to the point raised regarding the matter of the air-break switch, I will explain that I put that point in for this reason: While fundamentally, of itself, I do not believe the air-break switch or the oil-break switch is responsible for any transients of high or low frequency, whatever, it is a fact that when connected to circuits of certain characteristics, they will produce transients, and vicious transients. You can make a test on a certain circuit with an air-break switch or an oil-break switch, and show a man that there are no transients, and yet, that man, if he knows his game, will make up other circuits and show you some of the worst transients you can imagine.

Mr. Howes made a good point as to lightning arrester connections. The average man takes his lightning arresters, and connects them 150 feet from his nearest transformers, and hooks up an inductance there. The results are that every time there is an arrester discharge, a wave of approximately two million cycles highly damped goes out on the line and subjects it to wave fronts approximately a half cycle of two million cycles, and that is pretty steep. You try to plot a two million cycle wave, and you will find it is pretty nearly straight up and down when it hits. The impact goes inside the insulator and tears into the porcelain a distance depending upon the time and the steepness of the wave front and maximum value of voltage. In that way, I think a great many of the lightning arresters, as they are connected up, are a menace to the lines to which they are connected. I think they are certainly a menace to the telephone lines along side of them. Now, referring to the matter of air-break and oil-break switches, the air-break switch has, I think, more tendency to cause oscillation for this reason: The oil switches operate on a few cycles, while the air switch sweeps away out, and there is a great deal more chance in that time for one current to break before the others. If that happens, your lightning arresters may operate on double voltage, a two-million-cycle wave will rush out on the line and into the first insulator it happens to catch in a bad place. That is the reason I brought in the question of the air-break switch. It is not fundamentally a question of the switch. It is a question of the tendency to transients in certain circuits to which it is connected. It is not so much a question of the air-break or oil-break switch as it is the circuit to which it is connected, and the method by which it is connected. I think Mr. Howe's point as to the manner of connecting up the lightning arresters is very valuable, and I know a great many of the lines I have investigated present a situation such as he described. In one line I know of in the Northwest, every time they charge a lightning arrester at one end of the line, the transient impulse will jump seven turns on the inductance at the other end of the line, and the men will stand around and say "they are charging down at the other end of the line." That could be stopped completely by changing the connection of the lightning arrester, so that there would not be a circuit there oscillating at that frequency everytime the lightning arrester was discharged. Now, as to the matter of flux concentration, that particular insulator shown in Fig. 1, was chosen because the variation in flux concentration was seven to one. Take the analogy of the beam. Part of the porcelain was working at maximum stress, and that was the part on which the whole thing depended. If you could have kept your wires as far from this inner petticoat, as they were with the outer petticoat on, you could just as well have done without using the outer petticoat, because it was not doing anything.

As to the matter of metal coating, which was suggested. I have found a transient puncture on the insulator taken off the high line, wherein I imagine the end of the tie wire was struck against the insulator and probably struck the glaze. I think it would be an extremely valuable point if a complete metal cap could be put over the top of the insulator.

The question was brought up as to a great many of these insulators being out on the line a long time and failing mechanically, but not electrically. When we took one insulator off the line, we took the petticoat out intact and split it, and took hold of it, and just broke a ring right out of it at that zone of flux concentration. You could break it with your fingers. I think a great many of the difficulties we have with our insulators are due to that point of flux concentration. There are two different forms of porcelain in that zone, so it is bound to weaken the insulator mechanically. The protection against high voltage is another problem that sounds easy. Mr. Howe's suggestion is a good one, but here is the trouble: You take a horn gap and put it up on the line, and if you put steep wave fronts on it, they may never pass across it. An ordinary horn gap will not pass certain transients. A needle gap probably will not pass one of a higher frequency than half of a 100,000-cycle wave. I think the ultimate solution will be found in the equipment which will be used this winter in a couple of places—as experiments—a sphere-gap horn gap. That is, the gap will be a sphere gap, passing any transients, but you will still have the old horns. Unquestionably, there are transients, sustained waves, or damped waves that go right by our lightning arrester horn gaps, and those get into our machines. For instance, there is the case I spoke to you of, where the inductance turns are jumped by the transient. It goes by the horn gaps and jumps seven turns on the inductance, because of the sudden banking up of wave by the inductance, so it is pretty clearly proved that you can get a condition of that kind.

Prof. Ryan spoke of the fact that we should have non-porous porcelain. I may be pessimistic in that regard, but I do not believe that non-porous porcelain can be made. Consider for a moment the value: A tenth of one per cent porosity renders an insulator worthless after it has been soaked a while, and a tenth of one per cent porosity is a pretty small margin to work to. You may be able to make such porcelain in the laboratory, with a vacuum furnace, but when you come to manufacture insulators in car load lots, it is a pretty close limit to work to.

In the matter of the punctures in the porcelain, some go half way through the porcelain and stop. That is, their time of duration at maximum voltage was not great enough to get clear through. Under the microscope, following these out one by one, you will very often find a puncture going in, then, there will be a branch. Now, whether or not that forked branch occurred with the first impulse, or whether the next impulse caught it and followed it along, and then broke off, I don't know. Now, enough of these minute punctures finally occur so that the combination of punctures brings about disintegration which reduces the resistance of that path until the power voltage passes through. I do not believe, from my investigation, that the concommittant occurrence of the power peak and the transients, is necessary for puncture. I believe that the transients will keep coming until you get a voltage that will break through. Insulator No. 3, mentioned in the paper, was taken off the line after insulators Nos. 1 and 2 were punctured. We took it off the line and it punctured under the flash-over voltage that it had successfully withstood before. It was a good sixty-cycle wave, with a 100-kilowatt transformer behind it. A 100-kilowatt transformer does not surge on one insulator. That insulator, on a 60-cycle wave, with a 100-kilowatt transformer, punctured under the flash-over voltage, indicating that it had been weakened materially by the impact of these transients. So, a voltage lower than normal operating voltage punctured the insulator.

With reference to Mr. Merwin's remarks about co-operation. It is a little discouraging to a man in a University with a laboratory at his command to sit down and go into a thing, and then go out and tell an operating man that a condition exists in which he will get such a result, and have that man laugh at you, and then about six months later, that man comes to you, and says 'I have had such and such a thing happen on my transmission line. What is the matter"? And it does not make him feel any better to have you tell him that six months or a year before, you had told him that that very thing was going to happen. It is my experience that it is very seldom that a man from a University laboratory can go to a power man and get any co-operation in making any tests on a power line. We would appreciate a little more of Mr. Merwin's spirit of co-operation in our work in the laboratory.

E. E. F. Creighton (communicated after adjournment): Mr. Peaslee has undertaken research work in one of the most important subjects in transmission engineering today. There is great need of more investigators in this subject and to get definite results it seems necessary for the investigator to enter the field of ceramics. Personally I have come to the conclusion that electrical testing alone will give comparatively little data of value.

Mr. Peaslee's photographs are interesting and I find myself in agreement in general with his conclusions. It is desirable that all the workers in this line come to a common agreement and language and with this in view I should like to ask questions about certain features of the work.

Taking the subject in the order of the reading—I find that certain mathematical calculations give one impulse in 15,000,000 random impulses within that part of a half-cycle of the 60-cycle wave, which is above the effective value. I have been unable to arrive at the same conclusions. For example, the potential of the wave is above the effective value from 45 deg. to 135 deg. or 90 deg. of the time. Therefore, random shots should fall, one in every four, within the range designated, since the ratio of time is 90 deg. to 360 deg. total. Such random shots could be obtained only by using a separate source of a-c. potential. If the same source of a-c. potential is used the shots will not be at random but should be located at a fairly definite point of the a-c. wave.

Referring to the notes under method, I should like to inquire if the regular 60-cycle tests were made on these insulators before the high-frequency impulses were applied; also if the ohmic resistance of each skirt was taken.

In the discussion on the failure of Insulator No. 1 Mr. Peaslee touches on a subject in which many tests have been made. Back of all these tests is the question which has been raised repeatedly in the past few years—what constitutes a fair test on an insulator and when does the test damage good porcelain? If the porcelain used in Mr. Peaslee's tests was good then the very mild test was too severe. I have made numerous tests which show that this impulse test was too mild to give a satisfactory test for porcelain insulators and therefore the tests show, unmistakably, a poor grade or defective porcelain.

In tests on insulators similar to Fig. 1, giving the fan-shape discharges, as shown in Fig. 2, it has been determined that the inner skirt was cracked either before the test or by the test, and that the discharges leaving permanent traces of their paths on the broken surfaces of the inner porcelain are due to the currents which pass through the inner skirt and charge up the condenser formed by the outer skirt. If both skirts are punctured, 30 kv. of potential would surely maintain an arc through the tiniest possible puncture hole. The current flowing through the inner skirt to charge up the outer skirt as a condenser is of the order of 15 amperes effective, the calculation being made for a damped wave of 750,000-cycles frequency, a voltage of 80 kv., and a capacitance of 40 micro-microfarads. As to the cause of the fan-shape discharge—I have come to the conclusion that it is due, not to the sealing up of the path, but to the lowering of the resistance of the path. Assuming that there is a crack existing initially, the first disruptive discharge will pass through the air in the crack from one surface of the porcelain to the other and repeated discharges in this path will heat the porcelain to a temperature of partial conduction. In other words, this becomes a high resistance path. When the next discharge attempts to pass through this resistance the *IR* drop is sufficient to maintain full potential and therefore the discharge will take place through an adjacent path where it has free air to ionize. It will follow this adjacent path until it has heated it to a condition of partial conduction and then choose a new path. Each time there is a sufficient sealing up at the point of discharge and also sufficient opening up of the crack to make a new path desirable.

As a proof of this theory, two electrodes across which a disruptive discharge takes place may have a high resistance rod or pencil placed across the gap and the disruptive discharge will refuse to follow the path of the resistance material, but will jump straight from surface to surface through the air.

If porcelain punctures without a crack it is not difficult to permanently reseal it if the proper precautions are taken. If liquids can be used as electrodes it is possible to avoid carrying carbon or metal vapors into the discharge path and thereby destroying the insulation after the spot has cooled. A porcelain cup set in water and filled about a quarter full was punctured half a dozen times with an oscillator, leaving the discharge on about 5 seconds after each puncture. The puncture hole filled up with clear-colored glass and was subsequently stronger than the rest of the porcelain.

In endeavoring in single pieces of porcelain like a suspension insulator to observe the deterioration which may take place from disruptive discharges at reasonable potentials applied over long periods of time, insurmountable difficulties seem to be encountered in determining the progress of the puncture. My experience has been that when an insulator punctures I have found unmistakable defects which caused the puncture. For example, a definite air bubble or lamination due to defective pugging of the plastic porcelain is most frequently the cause. Or it may be due to a fold in the porcelain while it is being jiggered. Or it may be due to an excess pressure of a tool which squeezed out the moisture along a sharp corner which subsequently developed into a partial fault in drying and was not fully vitrified later in the kiln. Or if the kiln is accidently under-fired, every piece may be more or less porous and therefore defective in proportion to its porosity.

Theoretically it should be possible to use the difference in potential gradient of the inner surface and outer surface of the porcelain to determine, by means of damage to the inner surface by corona, when the test becomes too severe for good porcelain. Practically satisfactory results have not been obtained due to defects in the porcelain. After an endurance test of many minutes or even several hours which has caused a puncture, the porcelain cap has been sawed off and the porcelain surfaces exposed to examination. Very rarely are other scars on the rest of the surface found even with a microscope. Such scars, indicating the possible beginning of puncture, have been found as frequently on the outer surface of the porcelain as the inner surface. Since the potential gradient on the outer surface is only a fraction of the value at the inner surface these scars indicate defective porcelain. Once, in grinding off a scar with a carborundum wheel a bubble in the porcelain was uncovered at a greater depth than the scar. The corona was burning its way into the bubble.

Damage to good porcelain can easily be done by carrying the potential gradient above its safe value, but such a gradient could not exist on the inner surface of a porcelain insulator at 80 kv. with its diameter of 1¼ in. or more. Therefore, I have been led to the conclusion that with most of the latest design of insulators the trouble is due, not to the design so much as to defective porcelain, which brings the problem back to the ceramic engineer. I feel we can make very little further progress on the electrical side until porcelains of reliable qualities can be reproduced.

A test was recently made in an endeavor to determine if single impulses were not more severe on the porcelain than oscillatory discharges. Several million discharges of the damped wave at 200,000 cycles were made on a suspension insulator immersed in oil. The voltage was 80 kv. for part of the test and 100 kv. for more than two hours of continual discharge at 120 per second. The porcelain was not punctured. It was subsequently broken up but no damage whatsoever could be noted on its surfaces. This porcelain happened to be perfectly made. There were no bubbles or laminations in any of the broken pieces and it was extremely strong mechanically 'n resisting the blows of the hammer.

W. D. Peaslee: Referring to Mr. Creighton's remarks, I am very glad that he has called to my attention the error in the paper regarding the number of random impulses occurring within that part of a half cycle of the 60-cycle wave which is above the effective value. This statement should read as follows, "Using the part of the 750,000-cycle positive half-wave transient above the effective value, one out of every 1,500,000 such random impulses will fall on the crest of the 60-cycle positive half-wave."

The regular 60-cycle tests were made on these insulators before the high-frequency impulses were applied but the ohmic resistance of each skirt was not taken as our megger was out of commission at that time.

I do not believe that Mr. Creighton's explanation of the fan shaped discharge lines is the correct one for all cases as I have found a decided difference in character of these lines when they are formed by the discharges through a previously existing crack and when they are formed by transients puncturing the uncracked porcelain. In the latter case an examination of these discharge paths will show a complete tube of melted silica without evidence of a previously existing crack, while a discharge through a previously existing crack is more likely to show a groove nature, although the heat of the discharge may later fuse the sides of the groove in such a way that a microscopic examination is necessary to detect the difference. Grooves of this kind have been found with partially fused fragments, microscopic in size, almost entirely filling them. Referring to Fig. 14, when the conductor was removed from this groove there was not the slightest indication of a crack, though under the microscope it was possible to detect the entrance points of the punctures. The porcelain fractured very easily along the bottom of the groove and the discharge paths shown in Fig. 15 consisted of tubes of fused quartz glass.

I believe with Mr. Creighton that the problem is essentially one for the ceramic engineer, but do feel that electrical tests must always be the criterion by which insulators are to be accepted or rejected. Their duty is electrical and their fitness for such duty must, I think, be determined by electrical tests.

Presented at the 10th Annual Convention of the Association of Iron and Steel Electrical Engineers in joint session with the American Institute of Electrical Engineers, Chicago, Ill., September 20, 1916.

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UNDERGROUND DISTRIBUTION SYSTEMS

BY G. J. NEWTON

Abstract of Paper

The object of this paper is to show the importance of properly designing an underground distribution system for the district it serves and the particular service it is to supply. Simply placing the wires underground does not constitute an efficient system.

Underground distribution is the ultimate solution of the distribution problem that confronts every Electric Light and Power company operating in progressive towns and cities. The excessive cost of this class of construction, as compared with aerial construction, and the permanent nature of the system, warrant a careful study of the conditions and justifies a reasonable expense in the development of suitable plans for the system.

The financial success of an electrical undertaking depends on supplying efficient and reliable service in an economical manner, and in order to secure this result the distribution system must be carefully designed and properly installed.

The automatic substation, when perfected and adopted, will not only permit a great reduction in the number of ducts required and a lower first cost, but will provide more reliable service and bring underground distribution within the reach of many small companies where the cost of this class of service would not be warranted under the former conditions.

The suggestions offered in this paper are based on many years experience and are made with a sincere desire to aid those interested in this class of work, particularly in the design and installation of the first system in the smaller cities.

THE FOLLOWING facts and suggestions are based on many years experience with underground distribution systems, and are stated in the following article with the intention of showing the importance of careful and intelligent design as related, not only to the first cost, but to the economical operation and ultimate value of the completed system.

An inspection of many systems has made it evident to the writer that improper design is responsible for more faults than is poor construction, and it is with a sincere desire to aid others interested in this work, to avoid such mistakes in the future, that these suggestions are offered.

No two systems are entirely alike, and the conditions are different in every place; it is, therefore, impossible to formulate any definite rules that will apply under all conditions. The engineer must be guided by good judgment, based on experience, and a thorough study of the conditions in order to secure satisfactory results.

Owing to the increasing demand for electrical energy, and the serious objection to the unsightly and dangerous overhead wires and poles, underground systems of distribution have become a necessity in many places where the expense of this class of service would not have been considered warranted under former conditions.

Underground distribution is very expensive, as compared with overhead construction, and in many cases, particularly in the smaller cities, the first cost is of vital importance; a carefully worked out design is therefore necessary in order to derive the greatest benefit from the money expended. Many of the present systems have not been designed with the care, and attention to detail, that their importance deserves and frequently the cost of the system has been entirely out of proportion to its ultimate value.

The first installation of an underground system is made necessary by an order of the city authorities compelling the removal of poles and wires from certain sections of the city or by the desire of the operating company to improve the service and secure greater facilities in a district where the demand for light and power has reached a point that this class of service is warranted.

In either of the above cases, and in fact, practically in all cases in this country, underground systems are never installed until long after the district has been supplied by an overhead system. As a general rule, all overhead systems are the result of a series of extensions and changes, rather than the development of any systematic plan of distribution, and are seldom based on efficient or economical methods.

If it were possible to design and install an underground system at the start of an electrical undertaking the problem would be much simplified, as the station and consumers equipment could be selected, and the whole system designed for the most efficient results. Unfortunately the conditions are never so favorable, and the distribution engineer is confronted with many conditions over which he has no control, but must consider in making his plans.

Distribution problems are, therefore, usually very complex and permit of several methods of being solved. It is only by a careful study of the conditions and foresight as to the future requirements of the system that a satisfactory, economical and efficient design can be developed.

The conditions under which underground cables and equipment operate are more severe than on overhead systems, and a thorough knowledge of these conditions is absolutely necessary, and must be kept in mind, in selecting cables and equipment and designing the conduit system for their installation. Overhead wires can be, and frequently are, operated far above their rated capacity, without any serious danger, but underground cables and equipment must be operated within certain definite limits in order to avoid serious damage, if not total destruction.

Economy of distribution is equally as important as economy in production, particularly at the present time, when practically all public utility companies are regulated, to a greater or less extent, by state or municipal commissions. First cost is not, therefore the only factor that should be considered, as economical operation and reliability of service are equally as important in the financial success and growth of the business.

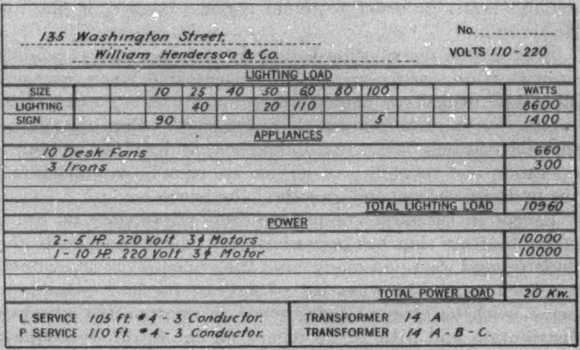
Except in the large companies, there is probably no branch of the business that has been given less thought and study than underground work; in many cases the principal object evidently has been to get the wires out of sight at the least possible expense, with no attempt being made to improve the system of distribution and little or no regard for the future development of this class of service.

The operation of an underground system, when properly designed, installed, and maintained guarantees the most reliable and efficient service of any method of distribution ever employed; the financial benefit, directly due to this class of service is, in many cases, a proof of the wisdom of its installation.

While it is admitted that underground systems are expensive to install, still it must be remembered that a conduit system is a permanent structure, has little or no depreciation; on the contrary it will increase in value as the importance of the section it serves is developed. Considering the first cost, permanent nature of the undertaking, and importance of economical and reliable service, it is advisable to make a thorough study of the conditions and future requirements of the service on which to base a design of the proposed system.

In designing an underground distribution system there is one important fact that must always be considered—the system should be designed to serve the entire district that can reasonably be expected to ever require this class of service. Such a design permits of a systematic scheme being developed for the whole district, uniform methods of construction, and standardization of equipment.

If this method is followed it is then possible to install any section, from time to time as the service demands, and each completed section will form a part of the whole general scheme and eventually develop into a system rather than a collection of more or less useful sections of conduit.



135 Washington Street.
William Henderson & Co.
No. ....
VOLTS 110 - 220

LIGHTING LOAD

SIZE			10	25	40	50	60	80	100				WATTS
LIGHTING				40		20	110						8600
SIGN			90						5				1400

APPLIANCES

10 Desk Fans	660
3 Irons	300
TOTAL LIGHTING LOAD	10960

POWER

2- 5 HP. 220 Volt 3φ Motors	10000
1- 10 HP. 220 Volt 3φ Motor	10000
TOTAL POWER LOAD	20 Kw.

L. SERVICE 105 ft. #4 - 3 Conductor.
P SERVICE 110 ft. #4 - 3 Conductor.
TRANSFORMER 14 A
TRANSFORMER 14 A - B - C.

Fig. 1

It is not the object of this article to show each step in the design of any particular system but rather to point out certain important features to be kept in mind and offer suggestions as to the general method to be adopted; it is only by a thorough study of each case that the best methods can be determined.

The first step in designing an underground distribution system is to secure an accurate load record for each consumer in the proposed underground district. This record should be kept on cards similar to Fig. 1; where there is a large power load in the district it is advisable to make separate records for the lighting and power loads, using different colored cards for each record.

The card shown in Fig. 1 is simply a sample, and the best arrangement of the inventory on the cards will depend on the requirements of each particular system.

The reverse side of the cards can be used for showing the number and location of the transformer supplying the service lateral, consumers fuse box and other information connected with each consumers service.

These cards if properly corrected will form a permanent record of great value in making future changes and balancing the load on the distribution system.

The men securing the load record should be provided with paper pads printed the same as the cards and the permanent card record can be made in the office from these slips and the cards be kept clean and neat.

A careful inspection should be made of each building to determine the most suitable location for the new underground lateral in order to reduce the cost of changing the inside wiring as much as possible. Except in the case of very heavy loads or consumers where emergency service must be provided for, it is advisable to supply all of the consumers in a building from one lighting and one power lateral, this reduces the number of laterals, handholes, and fuse boxes and permits using the least amount of copper by taking advantage of the diversity of a group of consumers.

The lighting and power load can be plotted on one drawing as shown in Fig. 2 or the loads can be plotted on separate plans, the latter method is best as the plans for each system can then be kept separate.

The load maps for each system should show the total load, both in the underground district and outside of it, that is to be supplied by cables in the conduit system from the power house so that ample conduit space can be provided and the most suitable routes and sizes of feeders determined.

Having the lighting and power loads and a map showing the street light system, the next step is to determine the most suitable plan of distribution to be adopted, this may be called the critical point in the design of a distribution system, for on the decision depends not only the first cost of the installation but the reliable, efficient and economical operation of the distribution system.

There are two general schemes of distribution:

1. To supply the whole city from one power house.
2. Divide the city into districts and supply each from substations, or rather from the power house and substations.

In many of the older systems the first method was used and a large number of ducts were installed, in one trench from the power house, to serve the whole city, or at least that portion that was to be supplied by underground eventually. This necessitated providing a large number of spare ducts, a large percentage of which remained idle for years and not infrequently resulted in too many ducts in some places and too few in others.

Not only was the first cost of such a system excessive but the manholes were almost invariably too small to accommodate the number of cables that could have been installed in all of the ducts had there ever been use for them. The most serious objection to this plan is that the losses due to the heating of so many cables in one conduit run are excessive and materially reduce the carrying capacity of the cables, particularly in cables occupying the inner ducts.

Another serious objection to this method is that a burn-out on one cable is practically certain to damage adjacent cables and cause interruption of service over a considerable area. Faults on underground systems usually affect more consumers than on an overhead system and require more time to repair, therefore, no system should be considered that does not permit being sectionalized and have reasonable emergency facilities provided for restoring service with the least possible delay.

The objections to the first plan, as stated above, preclude its adoption except in very small cities where the area to be served by underground distribution is limited, and the total number of ducts installed in one trench will not be excessive.

The second method of distribution, when properly designed, avoids all of the objectionable features of the first method and is particularly adapted to the modern practise of installing substations supplied by high-tension feeders, as each district is practically operated separate from the others and with suitable emergency feeders and switching equipment permits each district to assist the others in case of necessity.

The old saying "That you should not put all of your eggs in one basket" is particularly true if we change the words slightly—"You should not put all of your feeders in one trench or manhole" and the distribution engineer will be wise to keep this warning in mind as far as the requirements of the case will permit.

Reliable service and economical distribution are absolutely necessary for the financial success of every light and power company. Reliability depends on the following conditions:

1. The best material, equipment and workmanship.
2. Proper selection of material and equipment for the service it is to supply.
3. Efficient protective apparatus, judiciously installed.
4. Sectionalizing apparatus properly located.
5. Continuity of supply, by feeders over different routes or an arrangement that will provide at least two sources of supply for the network.
6. Regular and systematic inspection of the distribution system by competent men.
7. Accurate plans and records of the distribution system so that changes, additions and extensions can be made to the best advantage with the least possibility of error.

Economical operation depends upon a reasonable first cost, in addition to all of the above conditions, and where a system is designed at first for a whole city (keeping in mind future substations) it is possible to reduce the number of ducts and manholes to a minimum, install sections as the business warrants and extend the ultimate cost over a considerable period.

Keeping the above facts in mind the actual design of an underground distribution system should be made on the following general plan. Assuming that the first underground installation is to supply a district similar to that shown in Fig. 2, and that later this district will be extended a block or two in each direction and supplied from the main station.

While it is admitted that it is not possible accurately to foretell where substations will be located in the future, still a study of the conditions will generally permit a reasonable assumption to be made and if separate conduit is to be installed later for high-tension feeders this part of the work does not enter into the first design except in a general way.

After making the load maps for the lighting and power systems and also a map showing the location of the street lights it is a good plan to first layout the street light circuits, for assuming that all wires in the district must be placed underground it is evident that conduit must be installed to reach every light.

The location of the street lights is determined by the city authorities and can seldom be altered enough to materially change the conduit arrangement, therefore, by designing this system first it will give a general idea of where the conduit *must* be installed and keeping this plan in mind it is frequently possible to arrange the secondary mains so as to utilize the same routes

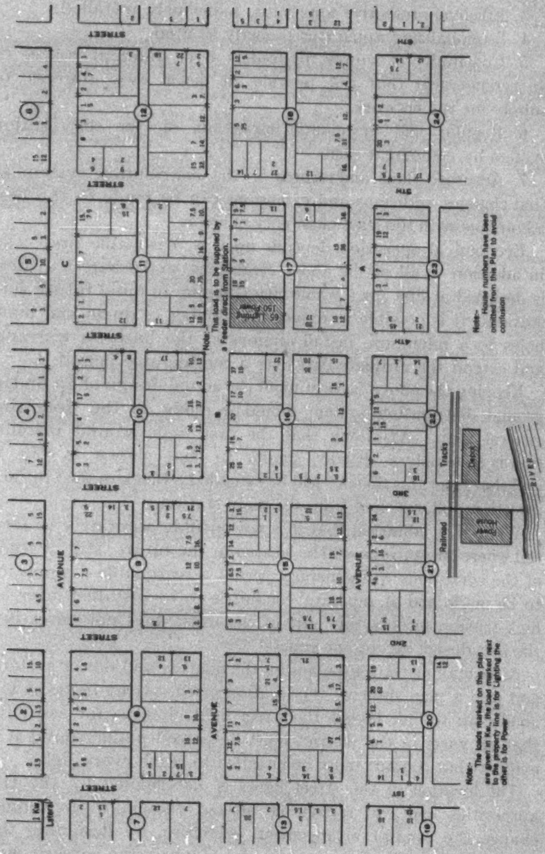

Note:- The loads marked on the plan are given in Kw., the load marked next to the property line is for Lighting the other is for Power
Note:- House numbers have been omitted from this Plan to avoid confusion
Note:- This load is to be supplied by a Feeder direct from Station.
65 Lighting
150 Power
1st
2nd
3rd
4th
5th
6th
STREET
AVENUE
A
B
C
Railroad
Tracks
Depot
Power House
River
1 Kw.
Lateral

Fig. 2—Load Map

(particularly in alleys and the less important streets) so as to avoid considerable conduit construction.

The proposed location of the laterals in each building should be shown on the plan for the secondary systems for light and power. A study of these locations together with the street light conduit layout will often show where slight changes in one or the other will permit considerable saving, even when changing some laterals will increase the cost of the inside wiring.

Owing to the fact that the grouping of consumers, in a district, will usually be different on an underground system than it was on the original overhead system it is practically impossible accurately to determine what the demand and diversity factors will be for the new system. A distribution system for either lighting or power usually consists of the following sub-divisions:

Primary feeders to centers of distribution.

Secondary feeders supplying the transformers.

Secondary mains supplying the service laterals.

Service laterals supplying the consumers.

In small systems the secondary feeders are not required, as the transformers are connected directly to the primary feeders.

The size of cables to use for the laterals is easily determined, the principal object is to restrict the number of sizes of cable as much as possible, using about three sizes for the whole system, and if possible, making the largest size used for laterals the same as one of the sizes used for secondary mains.

Aside from the laterals it is evident that the secondary mains receive less benefit from the diversity factor than any other part of the system. It is also evident that any increase in the load will directly affect the mains which must be large enough to maintain satisfactory voltage for all consumers connected to them.

On the one hand is the diversity factor tending to reduce the size of the mains and on the other hand the probable increase in load which must be provided for, tending to increase the size of the mains. As not only the first cost but the interest on the investment depends on the size of the copper, it is important that these two conditions be given careful consideration and it is in cases of this kind that the engineer must be guided by experience and his knowledge of the situation.

There is one point that should be remembered in determining the size of cable to install for secondary mains, particularly where they serve a number of consumers in a business district.

Owing to the fact that the service laterals are spliced directly to the mains at frequent intervals it is very expensive to replace them and the old cable, being in short lengths, is of little or no use except for its junk value; it is therefore advisable to make all secondary mains of ample size to provide for the total load that can reasonably be expected and use the best kind of cable, either varnished cambric or rubber insulated, for all secondary mains and laterals that terminate in junction or fuse boxes.

The load in the district should be divided as equally as possible into a suitable number of distribution centers so that one size and style of cable can be used for all of the feeders, as this permits standardizing the equipment and requires less cable being kept in stock for emergency purposes.

The feeders being generally small cable and having few or no taps on them can easily be replaced by larger cable and the old cable is in sufficient lengths to be used elsewhere. Instead of installing a larger cable to replace a loaded one it is generally better to install an additional feeder to another center of distribution, using the standard size of cable.

Where the requirements of the system demand the use of two-conductor cable it is advisable to have it made up in round form instead of the flat, or figure 8 style, as it is practically impossible to train this latter style without kinking it.

A careful study of the conditions under which underground distribution systems operate, particularly in medium size or smaller cities, has convinced the writer that the safest guarantee of reliable, efficient, and economical operation is to install cable and equipment, as far as the conditions will permit, under the following general rules.

Service Laterals. Use either cambric or rubber insulated cable, spliced directly to the secondary mains, and terminated in water-tight fuse boxes on the consumers property. (The number of laterals taken out at one splice will depend on the system; for single-conductor cables four laterals can be taken out, but two is about the limit where three-conductor mains and laterals are used.)

Secondary Mains. Make these cables of ample size to provide for all the growth that can reasonably be expected. Use either varnished cambric or rubber insulated cable for all secondary work where cables terminate in subway equipment.

Primary Feeders. These cables derive the most benefit from the diversity factor, are comparatively long lengths, and have few taps on them, therefore are less subject to damage than the rest of the cables and are easily replaced with small financial loss. Small reserve capacity is all that need be provided for this class of cables.

Paper insulated cable can be used to advantage frequently at considerable saving providing that the ends are properly terminated in compound-filled potheads or varnished cambric or rubber insulated tails used for connecting to the equipment.

Personally, the writer does not approve of using any paper insulated cable on distribution systems, except on cases where the emergency facilities are such that the failure of a feeder cannot cause a serious interruption to the service.

In small companies, where competent cable men are not always available, the use of paper insulated cable on the distribution system is not advisable, it is however, well suited for high-tension feeders and tie-lines.

Subway Equipment. Due to the liability of being submerged occasionally and the limited space usually available, for its installation, subway equipment is probably the most prolific cause of trouble on underground distribution systems, and the greatest care must be used in selecting and installing it.

The best insurance against trouble from this cause is to provide reliable sewer connections to all manholes and vaults in which subway equipment is located. Separate the primary and secondary equipment by placing the transformers, primary fuses and switches in a vault (preferably located under the sidewalk adjacent to the manhole in which the secondary junction boxes are located.) This arrangement reduces the length of the secondary mains, which are usually large expensive cable, and lessens the liability of a burnout on the primary equipment damaging the secondary network. See Fig. 3.

The object in placing the vaults under the sidewalk is that it is seldom possible to secure sufficient room in the street, also there is less liability of the vaults being flooded from surface water and they are more accessible in the winter when the ground is covered with ice and snow. This method of construction is more expensive than placing all of the equipment in the manholes but the added security is well worth the expense on an important installation.

Subway transformers should not be set on the floor of the vault but should be raised so that the air can circulate under and around them. Where more than 200 kw. of transformer capacity has to be installed in one vault it is advisable to provide ventilating pipes from the vault to a pole or side of a nearby building.

Subway junction and fuse boxes should not have slate or marble bases, but use ebonite or similar material that will not absorb moisture. All boxes should be subjected to an insulation test before being installed. Barriers should be provided between terminals of opposite polarity.

The iron work of all subway equipment should be permanently grounded to a reliable ground rod, plate, or if possible, to the city water pipe system. In large vaults, where there is considerable equipment, at least two ground connections should be provided.

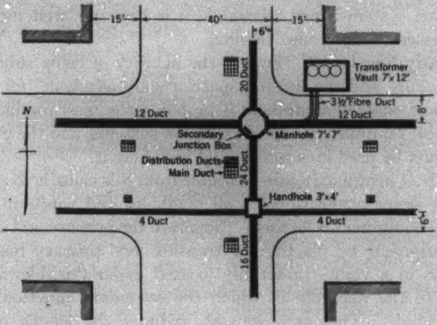

15'
40'
15'
6'
20 Duct
Transformer
Vault 7'x 12'
3½ Fibre Duct
N
12 Duct
12 Duct
8'
Secondary
Junction Box
Manhole 7'x 7'
Distribution Ducts
Main Duct
24 Duct
Handhole 3'x 4'
4 Duct
4 Duct
6'
16 Duct

FIG. 3

Installing Cable. Assuming that all cable has passed the usual factory test, it is seldom necessary to subject it to another test before being installed unless there is some evidence that it has been damaged in transit. The conditions under which the cable is purchased and installed will, however, generally decide this point.

Use skids in loading and unloading reels, never drop them off of the truck. Place reels as near the point where they are to be used as possible. When reels must be left on the street for some time they should be securely blocked or preferably wired to a pole to prevent their being rolled about. Care should be taken not to place reels where they will interfere with hydrants, or obstruct manholes, water gates or traffic.

Never handle paper insulated cable when it is cold. In cold weather it should be kept in a warm place until it is to be installed. Paper cable should not be bent shorter than eight times its diameter and should be warmed before bending.

Always provide sufficient men and power to safely handle cable during installation, when the cable is started in the conduit try to maintain an even steady rate of pulling. For heavy cable it is advisable to use grease or powdered soapstone.

Ends of cables should be kept sealed until ready to be spliced. Cables should not be left hanging from the duct mouth, but should be supported on hangers with as little bending as possible. The final bending and training of the cables should be done by the splicer when joining the sections.

When installing a new system, all lengths of cable should be bonded together temporarily as soon as they are installed. As soon as the cable system is completely connected up tests for electrolysis should be made of the whole system and proper measures taken to protect the cables in case of necessity.

The arrangement of cables and equipment in the manholes and vaults must be carefully planned to secure neatness and ample space in which to work and operate the equipment with safety.

All cables and equipment should be plainly marked showing the operating voltage and system it is used for. Where single-conductor cables are used on three-phase circuits they should be distinguished by different colors as this will prevent mistakes in making changes as only cables of like colors should be connected together.

While it is admitted that it is impossible to install a system that will be entirely free from trouble, it is possible, by carefully designing the system to prevent many of the faults that are a constant source of trouble on many systems.

Conduit System. The conduit system should be designed to serve the electrical distribution system as previously designed. This statement may, at first, appear to be a self evident fact, but unfortunately many conduit systems are not arranged to properly and economically provide facilities for installing the proposed cable system. It is not an uncommon practise to install a conduit system based on a general assumption of the actual requirements of the electrical system.

The writer has seen conduit systems in which it was absolutely impossible to install the distribution system as it had to be operated, and which had to be partially rebuilt before the cables and equipment could be installed. These are no doubt exceptional cases but it shows the importance of a definite method of procedure in designing an underground distribution system.

It is a common practise in designing conduit systems to select streets or alleys having the cheapest pavement in which to locate the conduit, and then attempt to fit the electrical distribution to this location, and the result is invariably unsatisfactory and the saving in the cost in repaving is frequently exceeded by the additional cost of cables, and the total cost of the system thus increased.

It should be realized that a properly designed and constructed conduit system is a valuable property, and a permanent structure having little or no depreciation, and its importance in the supply of electrical energy warrants the greatest care being taken in its design and construction.

Conduit systems that are to serve high-tension or tie lines between substations can be located so as to avoid the more expensive pavements, but conduit used exclusively for distribution systems should be located so as to best serve the electrical requirements regardless of the kind of pavement on the streets or alleys.

In a conduit system used exclusively for distribution (where all wires must be placed underground) the best location is usually in the streets. In cities having an alley in each block there is a strong tendency to locate the conduit in the alley.

The desire to utilize the alleys is based on the fact that the pavement is usually less expensive, and as the majority of pole lines are in the alleys the buildings are supplied from the rear, therefore if the conduit is located in the alley there will be less expense for changing the inside wiring to meet the new distribution system At first sight these advantages appear so great as to warrant the selection of the alley; there are, however, serious disadvantages to this location.

The alleys are usually from 16 to 20 feet wide and are generally fairly well occupied by water, gas and sewer facilities, and not infrequently, by one or two telephone conduit systems (which are usually installed before the electric light wires are placed underground) and the space available is, therefore, very limited.

The rear building line is very irregular, many buildings do not extend back to the alley, and frequently there are small sheds or extensions in the rear or the main buildings. The length of rear laterals would be greater than front ones and the difficulties and cost of installation considerably more; the greatest objection is that the rear laterals would not be permanent in many places but would have to be changed whenever any new building construction or changes were made.

Where alleys are located in the business section of a city they are usually used by the merchants for receiving and shipping goods and are subjected to a heavy traffic, considering the limited space. The merchants are practically all consumers of electric power and will strongly resent any interruption to their trucking facilities.

Owing to the limited space in the alleys, and the amount of traffic, it is practically impossible to store any material in them, consequently all material used on the conduit system must be stored in the adjacent streets and usually wheeled in by hand. This work and the excavation for manholes, removal of surplus material etc., will practically close the alley to traffic and the inconvenience of doing the work will greatly increase the cost of construction.

There is another serious objection to using the alleys. An average block, in cities having alleys, is about 300 by 300 ft. (91 by 91 m.) and usually has at least twelve separate buildings in it, in the business section there are generally more. When the distribution system is located in the alleys all of the buildings in a block are supplied from one secondary main which practically doubles its size, and the number of laterals that must be connected to it require frequent handholes in order to reduce the length of the laterals. This entails more complicated and expensive splices, cuts the main into short lengths, and in case of serious trouble puts the whole block out of service.

As a general rule, with the single exception of requiring less conduit, the alley construction is less desirable than a system installed in the streets. This statement applies to the business district of a city. Where overhead laterals can be used in a residential section the alleys are preferable for the location of the conduit, and as the traffic and obstructions are usually considerably less in such sections, the construction cost will be correspondingly less, depending on the pavement.

Before making the conduit design it is necessary to plot the location of all car tracks and existing sub-surface obstructions, in order to determine the most suitable location for the new system. While it is known that the records of sub-surface conditions are seldom accurate still a study of these records and the location of water gates, sewer manholes and other surface indications will permit a fairly accurate map being prepared.

Where there is any doubt regarding space being available for the conduit and manholes it is advisable to dig test holes, and if possible they should be dug at the points where it is proposed to locate manholes.

The design of an underground distribution system is not a difficult matter if handled in a systematic manner and the result obtained from a thorough study of the conditions will fully warrant the engineering expense necessary to prepare accurate plans covering every detail of the work.

DISCUSSION ON "UNDERGROUND DISTRIBUTION SYSTEMS" (NEWTON), CHICAGO, SEPTEMBER 20, 1916.

T. E. Tynes: This most excellent paper, prepared by Mr. Newton, and so very ably presented by Mr. Gear, covers the question of underground distribution of energy in a very broad way. Mr. Newton has given a great deal of time and thought to this question of underground distribution, and while the paper applies particularly to the distribution of energy in cities and congested districts, such as we have here in Chicago and in other large cities, the principles involved are applicable to any underground system which we may have occasion to use in steel mills, such as the construction of conduits, the making of joints, the position of switches, etc.

Alfred F. Hovey: A great deal of time might well be given to the discussion of this paper as regards the detailed construction of the conduits and cables. There is one statement which involves a rather dangerous point; the author states: "Where triplex-conductor cables are used on three-phase circuits, they should be distinguished by different colors as this will prevent mistakes in making changes, as only conductors of like colors should be connected together." I have personally encountered a good deal of difficulty from just that kind of a specification. It is almost next to impossible to make joints that will be serviceable for a long term of years, such as good joints should, and at the same time secure the matching of colors. The time has come when we are using large conductors in sector form, and under those circumstances it is still more difficult to match these colors. Very often it requires one of the conductors to be drawn through and between the other two conductors in order to match the same color, and there is no safe way of identifying the conductor and be sure you are right, except by making a test one way or another, without possible damage to the insulation. Jointers find they cannot make as good a joint where they attempt to match the colors. The cable has to be manufactured in a certain way, so that the lay is all one way, and the cable has to be pulled in, in a certain direction, and sometimes it is impossible to feed the cable into one of the manholes, but it has to be pulled by means of a series of blocks and tackles, but if the cable is not drawn in exactly right, it is extremely difficult to straighten out the lay of the conductors at the joint, so to match the conductors, although it sometimes happens; but then it is a matter of chance. That is one point which I think it might be well for engineers to avoid in making up specifications to secure a perfectly satisfactory operating system.

Another point where the writer of the paper says: "Personally, the writer does not approve of using any paper-insulated cable on the distribution systems, except in cases where the emergency facilities are such that the failure of a feeder cannot cause a serious interruption to the service." Several managers of works with which I am concerned at the present time, are installing paper-insulated cables both for economy and for good operation. A paper-insulated cable requires slightly more careful installation, but if properly handled, I believe in many cases that it will make as good insulation as either the rubber or varnished cloth insulation. It has been my experience that recently the majority of engineers specify paper cable. There is no particular reason for bringing up that point, as nearly all cable manufacturers are prepared to furnish either rubber or varnished cloth or paper insulation on their cables.

Just a word of commendation to Mr. Newton, who has had considerable experience along this line for years. We have known him, particularly in conduit work, and in cable work for years, and I believe that this paper will be of great assistance to engineers in laying out either a large or small system, because it gives the basis in foundation of fact for a specification that would provide a satisfactory operating system.

Not having read this paper carefully enough to know whether any mention is made of a scheme used considerably nowadays, that is to run the trunk ducts underneath the service boxes, I would say that this is an important feature in designing space for trunk feeders and secondary mains by building a handhole over the top of the lower trunk conduits and taking in only the top ducts, using them for distributing mains and secondary feeders. That is a point on a small system that is particularly important, as it cuts down the original cost of the conduit system materially. In that way, the small conductors can be exposed through these handholes for taps and the handholes can be constructed at very small cost and at large insurance over the other scheme of opening all the ducts into all the manholes.

There is one manhole that has cost, as I was informed last week, about $10,000 because the engineers originally did not make the manhole large enough. The manhole has been rebuilt eleven times, with the consequent cutting of cables and re-racking them around this constantly enlarged manhole. One of the operating engineers told me not long ago that his company was expending over $150,000 a year rebuilding manholes. That is a point that the engineer, in laying out an underground distribution, might well keep in mind, because it is well known that the cheapest real estate is that which you enclose by a manhole wall under the street. By making a large, generous manhole, you have plenty of racking space for the cables on the sides, with sufficient room on the side-walls for proper racking and proper bending, and the original installation will take care of the operation in the future much better than having to rebuild the manhole at considerable extra cost.

F. D. Egan: My experience with underground conduit work has been entirely in the steel plant, and I could not discuss Mr. Newton's paper from the standpoint of city construction. We have installed approximately 125,000 feet of underground conduits in our steel mill, and as far as the matter of trouble goes, I find that the underground system is more reliable and more dependable than the overhead system.

Another point that Mr. Newton brought up regards the high cost of underground versus overhead. While that might apply in city construction, if compared to the type of construction to be used in a steel mill, the cost is in favor of the underground. When we distribute power at 6600 volts, or higher, for safety reasons we would construct duplicate power lines and the cost of this would be higher using bare copper pole lines than it would be with underground system and lead-covered cambric cable.

That is the experience we met with in our construction. We have been operating on this system in some of our plants for from three to four years, and so far we have experienced no trouble from an electrical standpoint. We lost two cables adjacent to the power house, which ran parallel with the old buildings, and the trouble there arose from the discharge of steam traps; this heat entered the conduit system, raised the temperature and the additional electrical load caused a breakdown. After we removed the steam trap discharge, we experienced no more trouble.

Another advantage of the underground system is the point of safety. We have there the point of totally enclosing the electrical distribution line, and the one point which would come up there, regarding safety, would be care in determining the proper line to work on in case of opening up of the cable.

S. C. Coey: Mr. Newton has given us a very interesting description of the methods used in laying out an underground cable system for a city and has pointed out many of the valuable features of such an installation. While many of the fundamental principles are the same, when we apply these data to an industrial plant system and especially a steel plant installation in which most of our members are most interested, we have a special application which calls for special treatment.

Installations in steel plants are more analogous to subway equipment than to any other type considered in the paper. The liability of having underground ducts filled with water is always present in those steel plants built on the banks of rivers having a large rise during flood periods. This applies to most of the plants in the Pittsburgh and Youngstown districts. Where plants are installed under these conditions it is usual to make the yard level only a few feet above the maximum high water. This is done from practical considerations as every increased foot that the plant is above normal water level means that many more foot pounds of energy expended in pumping the large amount of water necessary in the modern steel plant. This condition makes it necessary to lay out a duct system with the idea in mind that the cables are subject to the liability of being under water at some time. In plants of this description the use of underground transmission even with varnished-cambric lead-covered cables is subject to possibilities of trouble that are serious and makes the advisability of installing it very questionable.

In transmitting alternating current in lead-covered cables it is advisable to confine all three phases within one lead sheath. When single-conductor lead-covered wires are used for this work there is considerable loss and possibility of trouble from sheath currents. If the sheaths are bonded the I^2R loss from the sheath currents amounts to about half the normal I^2R loss in the copper conductors so that this method of operating is inherently inefficient. As it is usually impractical to insulate all the cables from one another and impossible where flood conditions are to be met the three-conductor cables should be used. In this case we have all the heating effect confined within one sheath and cable ducts must be carefully watched to see that there are not points where they get excess heating from external points.

I have also pointed out in a paper before the Association of Iron and Steel Electrical Engineers that where grouped ducts are used, the heating effect from a center duct to adjacent outside ducts with only radiation to take care of heat dissipation is cumulative, as shown by the result of tests, and for this reason ducts should not be made more than two ducts wide.

In underground ducts around steel mills as I have noted before it is often found that the ducts are heated from some external source. This is usually when the duct passes close to heating furnaces of some kind, which are impossible to get away from entirely in this class of work. This type of service calls for special study in each case. In some cases forced draught through the ducts have been used with good results. I have found for this work that varnished cambric insulation is the only type that can be relied upon as the heat affects rubber very rapidly.

While an underground system is usually spoken of as the most permanent system, and is, in the ducts proper, I would raise a question when we consider the wire insulation, as air and porcelain are more permanent than paper, rubber or varnished cambric and these are the materials depended upon in the two systems respectively to maintain the insulation of the circuit.

The principal advantage gained by the underground system is the freedom from liability of trouble from lightning, pole failure, and obstructions against wires.

In steel plants the locomotive crane problem is the most serious in the last item.

The advantages the overhead system has over the underground system are flexibility, initial cost, wire insulation and speed of location and repair of trouble.

As I see it, both systems as used today have their drawbacks and for a steel plant installation I believe that the ideal system of transmission would be to have an open concrete duct with reinforced concrete roof, well ventilated, with insulated cables strung on porcelain insulators so arranged that an inspector could walk through the duct. This could be entirely underground where the high water mark allowed, or in some plants could be above ground and used for a line fence. This system of installation would give the advantages of both the present systems without any of the disadvantages.

T. E. Tynes: We have quite an extensive duct system, originally installed about ten years ago. Our plant is built on land that was a swamp and there is a great deal of filled-in land. We have experienced some trouble due to the settling of the ducts. In locating a duct line, especially in steel plants, great care should be taken that this line is installed where it will not be interferred with by future construction, as it is a very difficult matter, after a duct line is installed, to have to rip it up to make room for a new mill going in, or some other consideration arising, which is of sufficient importance to cause the ripping up of the duct system.

The selection of a suitable foundation on which to build the duct line is very important, as I mentioned the trouble we have had due to the settling of the land. We have had some cable nearly cut off due to the settling of the ground.

The type of duct, or material out of which the duct line is constructed, is also important. In our plant we constructed every circuit of vitrified duct, and we had some difficulty with cracking joints which has allowed one thing and another from the ground to come in, and these substances have eaten off our lead coating right where the joints are. We have been troubled considerably by electrolysis, and upon taking out cable we have found pinholes, hardly visible, and they would let water into the cable.

Another important thing is making the splice. To make a good splice you should have the joint thoroughly filled with a compound, allowing no air bubbles to be formed, as in time the air bubbles will cause deterioration of the insulation and produce a breakdown. We do not know the reason for it, but we have opened up joints and found where the air bubbles destroy the insulation, and that increases until it gets to the lead sheath and then the cable breaks down.

We use paper and lead-covered cables. We have had them in operation now on 2200 volts for ten years, and have had no trouble at all with this voltage. We have had trouble on our low-voltage cable due to electrolysis and improper making of the joints.

All of our 2200-volt circuits are underground, also a great deal of our 440-volt circuits and 250-volt circuits. We are now taking the 250-volt circuits and the 440-volt circuits and putting them overhead.

We feel that where an overhead line is properly constructed, good insulators, and line put up in a permanent way, that it is much better for transmitting low voltages than the underground system. There is less trouble, and what trouble we have can be seen and taken care of before it is too far advanced. In the case of the 2200-volt circuits, the question of safety comes in, and we put those circuits underground for that reason.

C. A. Menk: I do not think I have very much to add to the paper. It is very interesting. What are you going to do with your present installation? You have an old plant, and if you are going to add to that, what will you adopt? The first question which comes up is: "You have gone along for years with your overhead construction. Is it going to pay to put it underground?"

Another thing; in designing a new plant I think it will be actually necessary to know what is going to be added in twenty years from now, if placed underground, because it is hard to tell what may develop and how soon it will develop. As Mr. Tynes said, to make extended changes would be very expensive. Take a city like Chicago and other large cities. These cities are well established, and underground work can be put in that should be good for twenty-five years, probably fifty years, especially in the residence districts, but in the case of mill work it seems as if one would have to look ahead and make very extensive provision for added improvements in the future.

In installing an underground system on three-phase work, will it be advisable to put in the triple conductor, or single it out and put it in, in triangle form?

In installing underground work, would you put in a conduit system large enough under the present day engineering, so that you could pull out the cables and put in larger ones, to avoid having to rebuild your manholes? One of the speakers said that in one case the manhole was rebuilt eighteen times. To me that looks like very poor engineering.

T. E. Tynes: In reference to Mr. Menk's question, whether to install triple conductors, or single conductors, all our underground cable is three-conductor, even the 2200 volt up to 500,000 cir. mils, and as I said before, we have had no trouble from the insulation of the cable—it has all been joint trouble and electrolytic action on the lead sheath.

S. C. Coey: I have had some experience with an installation on which single-conductor, lead-covered cables were used on three-phase work. On investigation it was found that where the lead covers of the cables came in contact, the sheath currents made pin-holes in the lead and when moisture was present paper insulation absorbed it like blotting paper. In my opinion it is a good thing to keep away from single-conductor alternating-current transmission.

H. B. Gear: You referred to low tension, I suppose?

C. A. Menk: Yes, 440-volt circuit.

H. B. Gear: I quite agree with the suggestion that the cables carrying large current should be multiple-conductor in form. A case came to my attention just recently, in an industrial plant—not a steel mill, but a condition which is very similar—where there were thirty-two No. 00 cables that had to be carried a distance of 800 to 1000 feet from the plant to the point where the power was used, and in order to keep down the inductive drop on these circuits they had made them small, but they were all overhead, and the drop was something like 33 volts on a 220-volt system in that distance. If these cables had been placed underground and made three-conductor, with a separation of only perhaps an inch between centers, the inductive component of the drop would have been very much less and the system would have been far more satisfactory. As it was, they were unable to use any additional power at the other end of the line without stringing more copper, for which room was not available on the poles.

In general, single-conductor cables are somewhat preferable for high-tension work where the lines are used for distribution purposes, that is what Mr. Newton has called secondary feeders which are really primary distributing mains.

Where joints must be made more frequently, for connecting in transformers, it is easier to do that work on single-conductor than three-conductor, from the fact that the opposite polarities can be separated. Frequently that work has to be done on either live, or very close to live wires. In general, the cost of three-conductor cables is sufficiently less than single conductors, to warrant their use, often at the expense, as is sometimes done in manholes or other places where taps are made, of fanning out into three singles. If the manhole lengths are long, say four hundred or five hundred feet, it is usually cheaper to make an extra wiped joint in the manhole, going through with singles, in order to save the cost of extra lead that would be put in the conductors in the long cable line.

In regard to paper insulated cables, Mr. Newton's statement is very well considered. He agrees they should be used and can be used where experienced men are handling them, but his statement is that they should not be used where inexperienced men are handling them. In a large system, such as that in Chicago, we use nothing but paper cable, even for laterals and secondaries.

There is no difficulty whatever with high-tension cables in taking care of ends if they are provided with potheads, as Mr. Newton suggests.

With regard to the facilities which are provided for in emergencies, the pot-head is so arranged that it is an easy matter to have one cable act as a reserve for a group of cables, doing the same class of service, and the developments in recent years are quite numerous as compared with what we used to have to get along with in the way of emergency facilities.

In connection with the ventilation of transformer rooms, I notice that Mr. Newton suggests that any transformer room for 200 kilowatts or more should be ventilated. Our experience is that is rather a high limit. We have had a number of cases of 150 or 120 kilowatts, where in the summer time the ordinary air temperatures, especially like we had last summer, were enough to make these transformer rooms run up to 130 to 140 deg. fahr., and the oil temperatures correspondingly high, so that the insulation was in danger. It takes rather a liberal ventilating system in the form of intakes and ventilating flues, etc., to take care of such an installation during warm weather conditions, especially where the transformers carry load continuously on power installations.

With regard to the size of conduits, I think that especially where secondaries are to be run, and where a three-conductor cable is advisable, the conduit should be at least four inches in diameter. We have had considerable difficulty in Chicago, because of the fact that many years ago we adopted a three and one-half inch conduit as our standard size conduit. When we get up to the point where we would use large three-conductor 20,000-volt cables, we are limited to a diameter of three and one-half inches in the ducts, and 250,000-cir. mil cable is the largest we can get into it. That leaves about one-quarter inch clearance which is the least that is practicable, and lengths between manholes are limited to 350 feet in order to allow the cable to be pulled in.

In any case where large low-tension cables are to be used and where three conductors are desirable, I would advise that a 4-in. conduit would be advisable.

B. G. Beck: We have been working with one of these underground systems for a long while. I think when we put in an underground system we should take into consideration the condition of the soil. We have one that the hotter it gets the more it leaks, and the more it leaks the hotter it gets. A great deal of the heating depends on the depth of the installation.

As pointed out, we should take into consideration the proximity of the furnace gas mains and hot water return mains, which may be installed, and another trouble we got into was in following the standard practise that ordinary city engineers used in putting in their duct system. They have really an intermittent service, a period during the day in which their heat goes into the duct systems, and during the night it can be cooled off before getting another big load in the morning, and adding more heat to it. With our system, it is a steady service, six days in the week, and we add heat all the time, and that makes our service quite different from city service.

As to using 16 or 20 ducts in a line, I do not believe I would do it, with the amount of power we have to use in these ducts.

In regard to sectionalized ducts, it is difficult to run the ducts through the steel mill in any case. In most cases you have to run it between furnaces, and when you are running from one center of distribution you cannot sectionalize your ducts.

We ought to take into account the effect of one cable transmitting trouble to another. I believe that has been taken care of by these gentlemen in a very nice way.

I have been thinking of taking out the old duct system, and making a runway through the plant, with a reinforced cover over it, and ventilators about every twenty ft., with air ducts so arranged that we can utilize a fan in case of burnout. We had a serious burnout some time ago when the cables were up to 120 deg. cent., even those cables which were not carrying current.

With all the troubles to which the underground cable system is incident, there is one thing we must take into account. We have been transmitting about 15,000 kilowatts, 2200 volts, underground, and we have not had any loss of life. The prevention of such loss of life was the primary object in installing an underground system, and we also have not had any motor losses on account of storms or lightning. On some overhead systems with which I have been connected, and on one system in particular, we had a bad lightning storm and lost fifteen motors at one time. That kept us busy for some time. A couple of those motors were big ones on which the plant depended. We have not had any trouble of that kind, but have had trouble with cables. Some of them have been minor troubles, and only one very serious trouble, and the trouble I refer to now was in the case of a cable which started to go bad, and affected the adjacent cable, and that affected the rest of them, and we had our whole duct system hot.

Regarding the running of these wires underground. As was pointed out, when you support the individual cables on porcelain insulators, the question of induction comes in, and it is a question whether with large current carrying capacity we would not run into a lot of trouble with this induction effect, it might be better to install the lead covered cables in a duct system where you could go into it and ventilate it and get your gases out, in case they did blow up.

Barney W. Gilson: I would like very much to hear something from Mr. Gear in regard to the limitations as to size of three-conductor cables. It has been my experience that three-conductor cables larger than 500,000-cm. are very difficult to handle and install, however, we now have two 500,000-cm., 3-phase cables in operation, and have some 700,000-c.m., 3-phase cables on order. These last will be laid in floor duct, and not pulled through conduit, as were the 500,000-cm. cables.

Ludwig Hommel: Mr. Coey's plan of a tunnel on the ground instead of under the ground, looks very good, where it is possible to put up such a structure. In fact, I had wondered whether a conduit system with ducts laid on the ground in a few inches of concrete with handholes where necessary might not be feasible in mills having ground water near the surface.

Where a tunnel is used, the cables should be covered for their entire length, just as is done now for the exposed part of the cables in the manholes. It would be interesting to have Mr. Hovey tell us what is the latest practise, what material is now used for that purpose. If porcelain insulators are used for supporting the cables, the lead sheaths should be grounded to avoid any possible danger to the men handling or touching the lead sheaths.

The planning of the manhole layout is important to avoid unnecessary crossing over each other of cables in the manholes. If a diagram is made of each manhole before the cables are drawn in, showing how the cables will run across ultimately when the duct system is filled, it should result in much better work and avoid trouble in the manholes.

The trouble with cables, if there is any, generally occurs in the manholes where the cable has to be bent—the bending of a cable is an operation that requires skill and experience. If a burnout occurs, it is most likely there to involve other cables.

I believe that junction boxes were mentioned in the paper. It is my experience that they are a source of trouble, while joints are practically as safe as the cable itself.

I agree with Mr Hovey on the paper insulated cable. I believe that it is fully as reliable as rubber cable and the joints are at least as easily made, and perhaps more easily and safely than on rubber cables.

George T. Street: There is one point which has been brought out in regard to manholes: the tendency in the past has been to make the manhole too small. But there is another point which has not been mentioned, and I think it is important: the tendency to make too few manholes. Each additional manhole means additional jointing, but it means much less liability of mechanical damage to the cable in installing it on account of reduction in tension while drawing in, and I think that is one point which should be carefully considered in laying out any conduit system.

Fred H. Woodhull: There is one thing that will have to be guarded against pretty carefully in using the tunnel system. The tendency, where the cables are carried on concrete carriers, where they carry heavy currents, is to have them clamped in some way. They must be held, due to the magnetic effect. I call to mind an experience I had some years ago in connection with central station work in New York City, where a short circuit occurred back of the switchboard, causing some large lead covered cables to jump off of the cable racks. It is a thing which will have to be guarded against.

A. F. Hovey: In one of the oldest and best known methods for fireproofing cables in manholes against the explosion of adjacent cables, common rope and concrete are employed. The former is wound spirally around the cable with about 1 in. separation between the turns, and the cable and rope are then plastered with a one to one mixture of sand and cement. The rope provides a rough surface to which the concrete clings readily and gives a slightly flexible back-ground, which aids somewhat in preventing cracking of the fireproofing under a chance blow.

The workmen's hands have proved to be better than any tool for applying the cement for this type of covering. As far as the fireproofing qualities alone are concerned, this covering is satisfactory, but its removal presents a formidable task. Efforts to reduce this difficulty have been made by placing the turns of rope closer together and, except for the fact that rope is now rather expensive, this method of protecting cable is fairly satisfactory.

Another method of fireproofing is that in which asbestos millboard, cut into 3-in. strips, is wound around the cable and held in place by a fire proof paste, silicate of soda. This covering proved satisfactory as long as the manholes remained dry, but if water ran in and covered the cables, the silicate was dissolved and the asbestos loosened, dropping from the cable. Recently, on account of the difficulty in obtaining deliveries of asbestos millboard, asbestos listing, a woven material with a selvage has been substituted. This material can be purchased in the form of 3-in. tape and wound spirally around the cable, and the silicate of soda covering is used to hold it in place.

When material as expensive as asbestos is used for fireproofing cables, some provision should be made for salvaging the covering when it is removed from the cable. A simple and inexpensive way of doing this is first to wrap the lead sheath of the cable with strips of cheesecloth dipped in paraffine. One layer of cheesecloth is sufficient. Then when repairs are necessary, the asbestos can be separated easily from the paraffined cloth and taken off in long strips. If these strips of asbestos are carefully rolled backward during removal, they can be preserved and reapplied.

In what is perhaps the most recent method of fireproofing underground cables, a layer of paraffined cheesecloth is wound around the sheath and over this metal lath, covered with cement and cut into strips, is spirally wound. The cloth is applied as described above, simply to aid in removing the covering. The metal lath used is a wire mesh covered with brick-clay put on under pressure and baked, the resultant product being a web of small briquettes which can be applied the same as any wire or expanded metal lath. This makes an excellent foundation for the cement mortar, as it is porous and flexible. The cement can be applied with a trowel or by hand, forming the covering into a homogeneous mass. While this type of covering is somewhat more difficult to install than the asbestos covering, it is considerably less expensive, as calculated from the prevailing prices of material. It can easily be removed by breaking the cement covering with a hammer and cutting the metal lath with tinner's snips.

Whatever covering is applied should be considered good insurance against both mechanical and electrical trouble. The added application of paraffined cheesecloth under any of these types of covering insures the lead sheath against damage at the time the covering is removed for changes in the manhole cables.

I would add one more point in regard to the fireproofing. In constructing the manholes, the scheme of putting in slate slabs to carry the cable and the joint through the manholes, particularly in the oblong or egg-shaped type, seems to be a particularly desirable addition to the conduit system itself. It gives a good support, whether the cables are wrapped or not, from one mouth of the duct to the other side. It saves putting in a lot of hangers, and can be installed by putting in T-irons along the wall and the stone or slate slab can be in three pieces, one long piece under the joint, and a section on each side of the joint, and furnishes a good protection from one cable to the other.

T. E. Tynes: One speaker brought up the question of the number of manholes to install for the duct line. Be sure to get enough. In our new lines we do not bring out all cables in the same manholes, but only bring out one-half to alternate manholes. If we lose one set of cables in a manhole, we are only incapacitated to half the capacity of our cables.

We have also used the method of wrapping asbestos tape around them to protect them in case of a ground, and that is effective except where there is gas in the manhole. We have had several bad fires due to leaky gas mains near the conduit line, and the system would fill up with gas, and that gas would destroy anything put in.

If a partial ground occurs on one of the cables, the asbestos covering in the case of dry manholes is sufficient protection, but this will not work where there is dampness.

H. B. Gear: In regard to the subject of cable protection, we have used the rope and cement wrapping in Chicago for several years now, and I think we have avoided the trouble Mr. Hovey spoke of, (of having the cement stick too tightly to the lead sheaths) by using rather more rope than he described, that is, wrapping the rope so that the spirals almost touch each other. There has been little difficulty in breaking off the rope and cement when it was desirable to get at the cable to do work on it.

There was one point raised about the maximum number of ducts referred to—twenty ducts. I might explain, further, that when anything over perhaps nine ducts or ten ducts is put into one line, it is the practise in Chicago to separate the conduit system into two halves by putting three inches of concrete between the two ducts on one side and the two ducts on the other side, never putting more than four ducts in any horizontal row, and no duct is more than one duct away from the outside earth, from radiation. This additional barrier of concrete between the two halves of the system is then carried into divided manholes where the number of cables is sufficient to fill the duct system, and not more than eight or ten cables in that way go into any one manhole. The manholes are built in a staggered form, one-half of the conduit system going into one and the other half into the other.

In the vicinity of power houses, where large numbers of cables must be brought out, this problem was solved in our most recent installation by the use of 24-duct runs. These 24-duct runs came out of three or four different busses, and fanned out into 4-duct lines, going to a series of manholes which led out from three different conduit systems. Three conduit systems went in different ways to the station, and by doubling the manholes on each of the conduit systems, and fanning out a group of 4 from each of the 24 into the manhole, all of the cross-overs were taken care of underground and a system was devised by which a cable could be brought into any conduit system or by which we have no cross-over in any manhole.

With regard to the maximum size of conductor which might be put into a 3-conductor cable, I do not know that I can answer the question specifically. I have known of cables as large as 600,000-cir. mils being used. The real limit, I think, as I stated before, is in the size of the conduit which is used. With a 4-inch conduit system, I think there will be no difficulty in using three 600,000-cir. mils or possibly three 750,000-cir. mils conductors in one three-conductor cable.

In reference to using a tunnel large enough for men to walk through, I would be inclined to think it would be preferable, even if such tunnels were used for low-tension cables, to use 3-conductor cables carried on a rack rather than to use single cables carried on separate racks which would necessarily have to be three or four inches apart. The inductive effect as well as the safety of installation, would be bettered by the use of three-conductor cables.

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STEEL CONDUCTORS FOR TRANSMISSION LINES

BY H. B. DWIGHT

Abstract of Paper

The electrical tests of some steel conductors of moderately large size have been published, and they indicate that there is an opening for the profitable use of steel cables on the branch lines of power systems of all voltages, in the same way that small steel conductors have already been used on branch lines at low voltages. Mechanical weakness or corona loss prohibits the use of small copper or aluminum conductors in many cases, and so steel becomes preferable.

Steel cables will not generally be economical on main transmission lines, except for long spans, and for high altitudes where corona is excessive. They may be advisable as bare conductors for direct-current railway feeders. They deteriorate more rapidly than copper conductors.

Steel cables for alternating current should be finely stranded and the different groups of wires should be spiraled in opposite directions. Fortunately, medium-priced grades of steel give better results with alternating current than some more expensive grades. The characteristic increase of resistance and reactance with increase of current or frequency may be valuable for limiting lightning and switching surges and short-circuit currents.

As there are large differences in electrical characteristics between different grades of steel, it is desirable that tests of medium priced steel cables manufactured in America be made and published, so that the data can be used in the designing of transmission lines.

THE RESULTS of a number of tests of the electrical properties of steel wires and cables when used as conductors of alternating current, have been published. Although these tests are incomplete, especially as regards the use of steel conductors in America, they show some attractive possibilities, from both commercial and engineering points of view, for the use of steel instead of copper in certain classes of work.

Attention is here called to the peculiar properties, the advantages and disadvantages, of steel conductors, in order to point out the advisability of making complete tests of American grades of steel, so that electric power companies may make use of this material for the cases where it proves economical and advisable for transmission-line work. Already, small sizes of steel conductors have been used with success in America, and this practise may be extended by a knowledge of the characteristics of large steel cables.

As is well known, the resistance of an iron or steel conductor is considerably greater for alternating current than for direct current. This is partly due to the skin effect, that is, the crowding of the alternating current to the outside parts of the conductor by the alternating magnetic flux in the conductor, and partly to hysteresis, or iron loss, caused by the alternating magnetic flux in the steel. In the case of copper or aluminum transmission-line conductors of usual size, the skin effect increases the effective resistance only one or two per cent and so is practically negligible. But in the case of iron or steel conductors, the flux has a magnetic path, and so attains a value from 20 to several hundred times as great as in a non-magnetic conductor. The result is that the skin effect is very pronounced and the effective resistance is increased by a large amount, in some cases by 100 or 200 per cent or more. However, the conclusion should not be assumed that steel cables are unsuitable for alternating currents. The tests so far published go to show that it is as necessary for an iron a-c. conductor to have fine strands as for an iron core to have thin laminations. The tests also indicate that if the strands are moderately fine and are properly put together, the increase of resistance at 25 or 60 cycles may be kept down to a reasonably small percentage. This is shown in Figs. 1 to 6.

The curves shown with this paper have been derived from test curves published in the *Elektrotechnische Zeitschrift* of January 28, 1915. They refer for the most part to a grade of steel or iron, called H-oo, which is a medium grade recommended in the above article for alternating-current work. That its cost is reasonably low is indicated by the fact that two other grades of steel were tested, each stated to be purer and more expensive, and also to have greater skin effect, than the grade H-oo. Although the purer material has higher conductivity for direct current, it has also greater permeability to magnetism, which is a disadvantage. Thus the cheaper grade was found to be more suitable for a-c. work. The same conclusion was also stated in a recent bulletin, No. 252 of the Bureau of Standards, Washington, D. C., by J. M. Miller, who found that of the wires tested, the grade with the highest resistance to direct current had the lowest resistance to alternating current, and was also the least expensive. The tests on American steel wire described in the above bulletin show somewhat less skin effect than that of grade H-oo steel wires.

The tests on grade H-oo steel were originally expressed in centimeter units and were made at 50 cycles. The curves have been rearranged for English units and for 60 and 25 cycles, and put on a base of amperes per cable, so as to apply to American transmission-line conditions. The Bureau of Standards' tests described in Bulletin No. 252 show that at commercial frequencies the increase of resistance is approximately proportional to the frequency, and this property was made use of in making the above transformations.

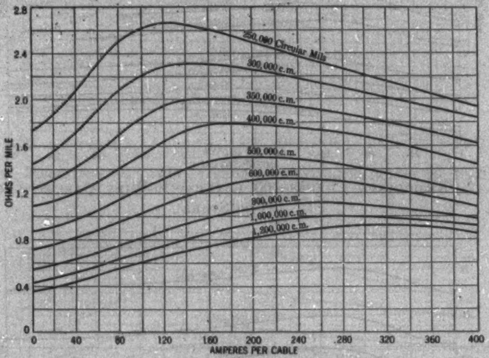

FIG. 1—RESISTANCE CURVES—60 CYCLES—49-WIRE CABLES—GRADE H-oo STEEL

The curves of internal reactance of steel cables published in the article referred to above, are shown in Fig. 7. These curves do not refer to grade H-oo steel, but to a grade of higher permeability. This grade, as shown by resistance curves in the original article, has more increase of resistance than grade H-oo, for the same size and stranding of cable. Presumably, therefore, grade H-oo would have somewhat lower values of reactance than those of Fig. 7. The tests show that the resistance curve and the reactance curve of a given cable reach their maxima at about the same value of current. It is of interest to note that increasing the number of wires in a cable decreases the reactance, while increasing the size of the wires increases the reactance, according to the examples in Fig 7.

The d-c. resistance of each cable is given in Fig. 7, and the maximum a-c. resistance will be about twice as great, according to Figs. 1 to 6. From the results shown in Fig. 7, the internal reactance at 60 cycles and at any current may be taken as being about 75 per cent of the a-c. resistance at the same current,

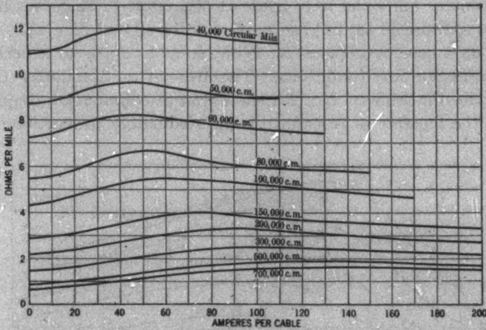

FIG. 2—RESISTANCE CURVES—60 CYCLES—19-WIRE CABLES—GRADE H-oo STEEL

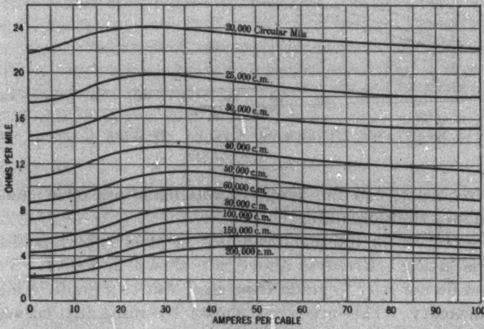

FIG. 3—RESISTANCE CURVES—60 CYCLES—7-WIRE CABLES—GRADE H-oo STEEL

in the absence of more complete data. The external reactance should be taken from regular transmission-line tables and added to the internal reactance to give the total reactance. The above is the method by which the examples at the end of this paper have been worked. It is merely approximate, and the caution should be given that for practical designing, test curves of the resistance and reactance of the actual type of cable to be used should be employed.

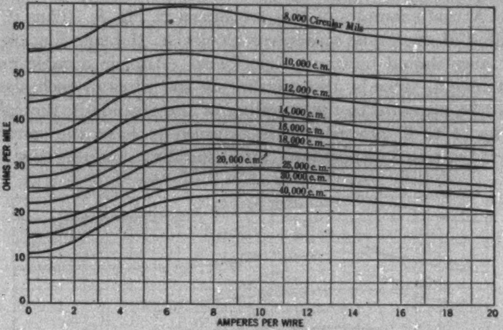

FIG. 4—RESISTANCE CURVES—GRADE H-oo STEEL WIRES— 60 CYCLES

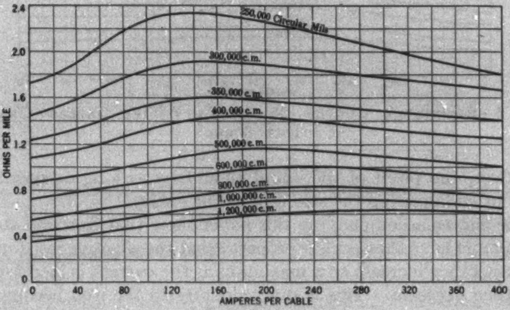

FIG. 5—RESISTANCE CURVES—25 CYCLES—49-WIRE CABLES—GRADE H-oo STEEL

Another point brought out by the tests in the *Elektrotechnische Zeitschrift* is that a large part of the magnetization is caused by the spiraling of the wires in a cable, and if the spiraling of the different groups of wires is properly reversed, the increase in effective resistance can be reduced as much as one-half. Actual examples of this are shown in Fig. 8. Thus if the spiraling of one layer of wires is clockwise, the spiraling of the next layer should be counter-clockwise. Also, in a cable made up of several strands, the spiraling of the wires in each strand should be opposite to the spiraling of the strands in the cable. In Figs. 1 to 6, the cables are assumed to have the spiraling reversed as much as possible. Since spiraling produces so strong an effect, the pitch of the spiral should be as long as possible without endangering the strength of the cable.

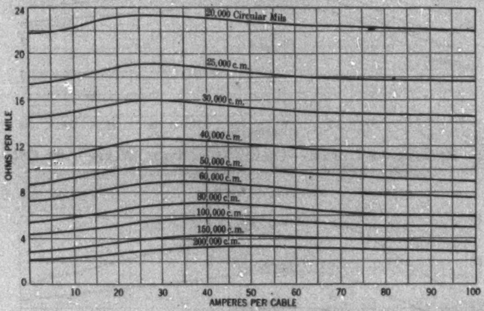

FIG. 6—RESISTANCE CURVES—25 CYCLES—7-WIRE CABLES—GRADE H-OO STEEL

The curves accompanying this paper show that iron and steel conductors have the peculiar property that the effective resistance and reactance increase to a maximum as the current is increased, and then decrease. This is due evidently to the iron becoming saturated so that the flux and the iron loss do not increase as before in proportion to the current. In most cases, especially with the larger cables, the decrease is very slow and the resistance maintains approximately its maximum value for most large values of current. This property should prove useful in transmission-line work, for the conductor will have a low impedance to the normal load current, but will have about twice as much impedance to the current flowing in case of a short circuit. The impedance will also be large to high-frequency surges caused by switching or lightning. It may prove more economical in certain cases to protect a line against short circuits and surges by using steel conductors than by installing current-limiting reactors or by increasing the reactance of the transformers.

This property may also be of use in the case of feeders of direct-current interurban railways. If the feeder be a steel cable it will have low resistance to direct current, but high impedance to alternating currents. It will therefore tend to damp out the suddenness of short circuits, and lightning surges, which cause synchronous converters and generators to flash over. That there is need of taking precautions against flash-overs in this way is shown by the fact that it has already become the practise to make the nearest connection between a feeder and the trolley wire several thousand feet from a synchronous converter or generator so that the latter will be protected by the resistance of a long stretch of feeder in case of surges or short circuits.*

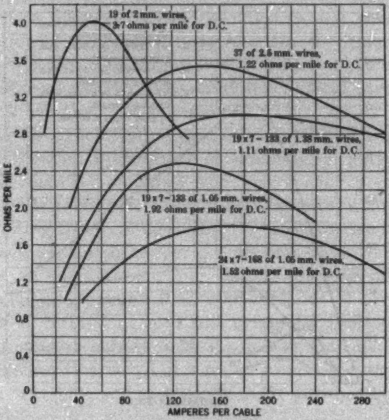

FIG. 7—INTERNAL REACTANCE CURVES—60 CYCLES—GRADE S.S.W STEEL

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*The Relation of Trolley-Feeder Taps to Machine Flash-Overs, by Chas. H. Smith, *The Electric Journal*, January, 1915.

If the feeder be made of steel, and especially if the stranding be coarse, the required protection will be still more complete. Steel conductors would probably be economical only where it is allowable to use bare cables, for the large size of steel cables compared with copper ones would greatly increase the cost of the insulating covering.

The higher conductivity of steel for direct current than for alternating current makes the use of bare steel cables for d-c. feeders more economical than for a-c. lines. A steel cable has about eight times as much resistance to direct current as a copper cable of the same size, and therefore seven times as much resistance as a copper cable of the same weight, since copper is more dense than steel. But galvanized steel cables usually cost less than 1/7 as much as copper cables per pound, and so should be more economical, other things being equal.

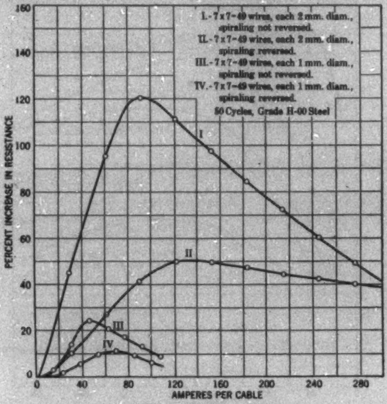

FIG. 8—EFFECT OF SPIRALING

Steel cables have frequently been used on transmission lines for long spans up to 3000 feet or more. In some cases the steel cable has been the support for a copper conductor, but in many cases the steel cable itself has carried the electric current. Such applications are of such a short length compared with the entire transmission line that they have been chosen, not because of a comparison of the cost and conductivity of steel and copper, but because copper or aluminum would be too weak for such long spans, and a much stronger material, like steel, was absolutely necessary in order that the transmission line should be mechanically safe.

Another application of steel conductors which has already met with success is for small size conductors, as mentioned in the second paragraph. Here again it has not been the relative conductivity, but the greater tensile strength, which has induced the choice of steel rather than copper. It is not the practise to use a smaller copper wire than No. 6 (0.162 in. or 4 mm. diameter) for overhead lines, because any smaller copper wire would be mechanically too weak. But it is often profitable to supply a small load at a distance of several miles, which would require only a fraction of the conductivity of a No. 6 copper wire, and in such cases a No. 8 or larger steel conductor has been found to have sufficient conductivity and mechanical strength, and to cost much less than No. 6 copper.

According to a description recently published,* a large 60-cycle power system in the State of Washington makes use of a considerable quantity of No. 8 iron wire for short tap-offs and lightly loaded branch lines on 6600-volt circuits, without serious trouble resulting from voltage drop. This iron wire is of course far cheaper than No. 6 copper. One line built by the above company is an example showing that it may be profitable to supply a surprisingly small load at a distance of several miles. This line is 10 miles long and was originally built with No. 8 copper clad steel to supply a 50 h.p motor load at 6600 volts. The line afterward carried 110 h.p. for some time and was later changed to No. 6 copper in order to have a capacity for a still greater load.

An example from Minnesota shows the use of a somewhat larger steel conductor. This line operates at 40,000 volts, 60 cycles, and is 20 miles long. No. 4 galvanized steel cable, made of 3 wires, is used. The load is about 300 kv-a.

The above examples show that a power company can build up new loads by sending out to considerable distances numerous inexpensive lines, using small steel conductors. The cheapness of the lines and of the outdoor transformers makes a very small load profitable, and the chances of obtaining larger loads are increased by building lines into new territory. Most of the small steel

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**The Electrical World*, p. 469, Aug. 28, 1915. See also similar examples described in the *Electrical World*, p. 820, April 8, 1916.

conductor lines appear to use solid wire of the kind which has been developed and sold for telegraph and telephone work, but a stranded cable would seem, according to the tests referred to in this paper, to be more suitable for a-c. transmission of power.

A line with small conductors, where steel is cheaper to employ than the minimum size of copper, is described in Example I. Here, a seven-mile steel line can be designed for 75 kv-a., but the smallest copper line that can be designed would be rated at 750 kv-a. Thus, while the poles and insulators will be the same in both cases, the steel conductors will cost only $220 against a cost of $2600 for copper. It is this large difference in cost which has been the main reason for using steel conductors on the branch lines of the power systems previously mentioned. This difference in cost of course is greatest when the price of copper is highest.

Besides being cheaper than the copper cable for small branch lines, the steel cable has the advantage of being mechanically stronger and less liable to be burned through by arcs. The steel line has therefore greater reliability at times of wind and sleet storms and at times of electrical breakdown or trouble. Steel cables are subject to the disadvantage that their useful life is shorter than that of copper cables, especially near the sea-coast, where galvanized steel is more quickly oxidized.

Example I shows also the advantage of using fine stranding. The seven-wire steel cable gives 9.6 per cent drop, while a solid steel wire of the same cross section has 12.5 per cent drop at the given load, according to the tests of grade H-oo steel.

Examples II and III show comparisons at 60 and 25 cycles between steel and copper conductors in regular transmission line work where the conditions are equal for competition between the two materials. The price of copper cable per pound may be assumed as being 10 times that of galvanized steel cable. This ratio is a usual one, being approximately true for times of low prices of metals as well as times of high prices. The lack of data on the reactance of a steel transmission line makes comparisons somewhat uncertain, but from the available data it seems probable that, considering the line complete with towers and insulators, it will cost for 60 cycles quite as much to use steel conductors as copper, for heavy transmission-line work, where the extra weight of steel cables is troublesome. For 25 cycles there may be a saving by using steel. However, there are many cases where the extra strength and size of steel cables are advantageous, and so at present the chief attention should be given to the classes of work where steel can show other advantages than merely low cost on a basis of carrying capacity for alternating-current power.

A transmission voltage of 100,000 or more is now fairly common. It is also a matter of observation that the cost of high-tension substations of the above voltage is decreasing, especially where outdoor substations are used. It is not possible to use a small copper or aluminum conductor on a 100,000-volt line on account of corona loss, as is indicated by the corona limits of voltage given in examples II and III.* Therefore the phenomenon of corona puts a limitation on the smallest allowable conductor of a 100,000-volt branch line, in exactly the same way that mechanical strength fixes the minimum size of wire for a low-voltage line, as previously described. Therefore, steel conductors have an opening for use on branch lines supplying a few thousand kv-a. on net works of 100,000 volts and higher. This is especially true in mountainous districts, where corona limits of voltage are lower, and where the other advantages of steel lines, namely mechanical strength and ability to resist burning by high-tension arcs, are especially valuable. In rugged country, also, the long spans permissible with steel cables may often save detours, and shorten the distance of transmission. There is also the probability, previously mentioned, that where steel conductors are employed, lightning and switching surges will be damped out more than where copper conductors are used.

In conclusion, it has been shown that large steel cables, if properly manufactured, can be used for carrying alternating currents. It appears that the chief opportunity for the use of steel conductors is on branch lines, where the size of copper required merely for the electrical load would be too small to use. However, in all cases, steel conductors will be nearly as cheap as copper ones, if not more so, and the use of steel will always increase the reliability of the transmission system.

EXAMPLE I

Length of line	7 miles
Voltage at receiver	11,000 volts
Frequency	60 cycles
Power factor of load	85 per cent
Phases	3

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*These limits have been calculated according to the tables in "Dielectric Phenomena," by F. W. Peek, Jr., page 210, McGraw-Hill Book Co., New York, 1915.

A.	Conductor	7-wire steel cable
	Size	25,000 cir. mils
	Diameter of cable	0.18 inches
	Diameter of wires	0.06 inches
	Resistance per mile at full load	17.6 ohms
	Full load	75 kv-a.
	Voltage drop at full load	9.6 per cent
	Weight of conductors	7300 pounds
	Cost of steel cables at 3 cents per lb	$220
B.	Conductor	Single steel wire
	Size	25,000 cir. mils
	Diameter	0.158 inches
	Resistance per mile at full load	23 ohms
	Full load	75 kv-a.
	Voltage drop at full load	12.5 per cent
	Weight of conductors	7300 pounds
	Cost of steel wires at 3 cents per lb	$220
C.	Conductor	Single copper wire
	Size	No. 6, 26,250 cir. mils
	Diameter	0.162 inches
	Resistance per mile	2.14 ohms
	Full load	750 kv-a.
	Voltage drop at full load	9.5 per cent
	Weight of conductors	8800 pounds
	Cost of copper wires at 30 cents per lb.	$2600

EXAMPLE II

	Length of line	75 miles
	Voltage at receiver	60,000 volts
	Frequency	60 cycles
	Phases	3
	Power factor of load	85 per cent
A.	Number of circuits	2
	Conductor	49-wire steel cable
	Size	400,000 cir. mils
	Diameter of cable	0.81 inches
	Diameter of wires	0.09 inches
	Full load per circuit	2500 kv-a.
	Resistance per mile at full load	1.16 ohms
	Voltage drop at full load	9.6 per cent
	Weight of conductors for two circuits	2,510,000 pounds
	Corona limit for operating voltage at 1000 ft. above sea level	164,000 volts
	Sustained short circuit kv-a. at full generator voltage, transformers with 5 per cent reactance being included at each end	4.4 times full kv-a
B.	Number of circuits	1
	Conductor	49-wire steel cable
	Size	1,000,000 cir. mils

	Diameter of cable	1.28 inches
	Diameter of wires	0.143 inches
	Full load	5,000 kv-a.
	Resistance per mile at full load	0.54 ohms
	Voltage drop at full load	10.9 per cent
	Weight of conductors	3,140,000 pounds
	Corona limit for operating voltages, at 1000 ft. above sea level	230,000 volts
	Sustained short circuit kv-a. at full generator voltage, transformers with 5 per cent reactance being included at each end	3.8 times full kv-a.
C.	Number of circuits	1
	Conductor	7-wire copper cable
	Size	No 1, 83,700 cir. mils
	Diameter of cable	0.328 inches
	Resistance per mile	0.678 ohms
	Full load	5,000 kv-a.
	Voltage drop at full load	10.7 per cent
	Weight of conductors	300,000 pounds
	Corona limit for operating voltages, at 1000 ft. above sea level	85,000 volts
	Sustained short circuit kv-a. at full generator voltage, transformers with 5 per cent reactance being included at each end	4.8 times full kv-a.

EXAMPLE III

Length of line		100 miles
Voltage at receiver		60,000 volts
Frequency		25 cycles
Phases		3
Power factor of load		85 per cent
A.	Conductor	49-wire steel cable
	Size	700,000 cir. mils
	Diameter of cable	1.08 inches
	Diameter of wires	0.12 inches
	Resistance per mile at full load	0.68 ohms
	Full load	4, 000 kv-a.
	Voltage drop at full load	10.2 per cent
	Weight of conductors	2,930,000 pounds
	Corona limit for operating voltage at 1000 ft. above sea level	215,000 volts
	Sustained short circuit kv-a. at full generator voltage, transformers with 5 per cent reactance being included at each end	4.7 times full kv-a.
B.	Conductor	7-wire copper cable
	Size	No. 2, 66,400 cir. mils
	Diameter of cable	0.292 inches

Resistance per mile	0.855 ohms
Full load	4000 kv-a.
Voltage drop at full load	10.2 per cent
Weight of conductors	316,000 pounds
Corona limit for operating voltage at 1000 ft. above sea level	76,000 volts
Sustained short circuit kv-a. at full generator voltage, transformers with 5 per cent reactance being included at each end	5.6 times full k-va.

DISCUSSION ON "STEEL CONDUCTORS FOR TRANSMISSION LINES" (DWIGHT) CHICAGO, SEPTEMBER 20, 1916.

Robt. E. Doane: Mr. Dwight has presented to us a comparatively new subject which has been little discussed by the engineering world in the past and which is of interest because of the possibility developed in certain directions. We would point out, however, as Mr. Dwight himself states, that the application is limited to certain special cases.

There are four general classes of service in which steel wire might be used to advantage.

1. Trolley wire.
2. Very lightly loaded high-voltage lines, which are not long.
3. Very high-voltage power transmission lines where the question of corona loss becomes of great importance.
4. Long spans.

In the first case the use of steel trolley wire has been quite extensively adopted in certain directions with somewhat variable conclusions as to its relative cost and general efficiency. In this field, the use of steel is restricted to certain sections of our large cities where the traffic is very dense and where the large portion of the current must of necessity be carried on auxiliary feeder lines, with very frequent taps to the steel trolley wire. In such special cases the resistance drop and consequent power loss in the steel as compared with copper is comparatively negligible, because the current has to flow along the steel but for a short distance only. Due to the greater hardness of steel, and its original first cost, together with its supposed longer life under operating conditions, it has had preference in certain cases. However, the very serious questions of corrosion and scrap value of the worn-out wire have to be taken into consideration and these are very important items which will be mentioned later.

There is another field of steel trolley wire where, as in such installations as on New York, New Haven & Hartford Railroad, it is necessary to have an exceedingly flat and smooth trolley wire for high speed work, in which cases the wire is sometimes suspended directly under a copper wire, purely for mechanical and not electrical reasons. In both of the above cases hard bronze wire is also used to advantage.

The second class of service, for which steel is applicable, is in the case of moderately high-voltage lines where very light loads are carried over distances that are not great. In such cases the smallest copper wire that would be used for mechanical reasons is, as Mr. Dwight mentions No. 6 B. & S., although in a great many cases No. 8 B. & S. has been employed for such service. This of course depends upon the climatic conditions, danger from high wind velocity, sleet and snow and distance between towers or poles, amount of allowable sag, and other considerations. There are undoubtedly cases where the smallest copper wire that could be used from the mechanical standpoint would be much heavier than would be necessary to meet the required electrical conditions of reactance drop and carrying capacity. In such cases the use of steel will be found to be economical, but here again the steel field is limited.

The third class of service, that of very high-voltage lines, where the question of corona loss becomes important is a field which has not yet been extensively covered in engineering discussion due to the fact that there are few such lines. There are probably not more than half-a-dozen such lines in the United States. Here again the field of application must necessarily be limited.

The fourth class of usefulness, that of long span work has been more extensively discussed. There are some notable examples of long steel spans, and some combination steel and copper cables such as the long span in use by the Mississippi River Power Company of Keokuk, Iowa, a discussion of which was printed in the PROCEEDINGS of the A. I. E. E. for October, 1914. It is well to point out that there are very few long spans which can not be made with a reasonable factor of safety using copper wire, provided that there is a possibility of allowing sufficient sag in order to somewhat reduce the tensile strain on the wire. The very slight increase in the percentage sag and consequent increase of the height of towers, which may be necessary in some cases, would make it mandatory for the engineer to decide on copper rather than steel. Of course in cases where additional expense in height of towers is made necessary the increase in the cost of steel towers may more than offset the advantage to be obtained from the use of copper in the span.

In making general calculations covering any particular installation, it would be logical to first assume that copper would be the natural metal to use and steel the unnatural, due to the fact that the vast majority of all transmission lines, trolley lines and long spans have in the past been constructed with copper and generally for good reasons. The percentage use of steel as compared with the copper is very slight indeed.

SCRAP VALUE AND CORROSION

There are two general conditions which make the use of copper generally mandatory, the principal one of which is the ultimate scrap value of the material used. By throwing out the consideration of fluctuations in the cost of metals, which is proper in a theoretical discussion, it may be assumed that the scrap value of copper is in the neighborhood of 85-90 per cent of the original purchase price. The scrap value of steel would probably be so low as to hardly warrant consideration, particularly if the line in question were a long distance high-voltage line extending across wooded or mountainous districts where the cost of salvage would be exceedingly high. The whole question as to the use of copper is an economic question, except for certain very special and rare cases. Lines are constantly being changed and altered and the scrap value is of great importance. It is of extreme importance in the case of trolley wire, which is frequently replaced and even if the copper trolley wire should be reduced 50 per cent in cross section, the scrap value may still be 40 per cent or more of the original cost.

The question of corrosion and life of the material is intimately connected with the scrap value. This is largely a question of climate, although the relative corrosion of copper and steel is probably about the same in most climates. It is unquestionably true that steel corrodes more rapidly than copper and its life is correspondingly shortened. In long distance transmission lines, one of the primary considerations is continuity of service, and if steel wire were used, subject to fairly rapid corrosion, it would necessarily be thrown out of consideration due to possibility of breaks occurring at unexpected times, perhaps many miles away from the nearest town, all of which would be exceedingly expensive and require a shutdown of many hours or even days before the trouble could be repaired. If copper lines are properly strung and not overstrained, this danger would be appreciably less.

Bear in mind that there are certain sections in the country where even the life of copper wire is comparatively limited and at best, lines have to be restrung quite frequently. In certain locations on the Pacific Coast the life of copper transmission line is but a very few years and in central Pennsylvania in certain localities, in the coke regions, copper is also attacked very rapidly by corrosion. Steel would probably go much faster than copper in such localities, and since the scrap value of copper is so enormously greater than the scrap value of steel, copper would almost of necessity be used under such conditions.

Mr. Dwight has mentioned the use of copper-clad steel wire which is being adopted in increasingly larger fields very rapidly. It combines the higher tensile strength of the steel, and offers 30 per cent or 40 per cent conductivity of copper as against approximately 14 per cent conductivity which the steel possesses. Its use has been very extensive indeed in the small size conductors and it has given a very satisfactory account of itself.

In discussing the commercial aspect of the case we note that Mr. Dwight has stated that the price of copper per lb. may be assumed as being ten times that of galvanized steel cable. If the present relative cost of copper and steel is a criterion, this ratio is hardly a fair comparison, for copper is in the neighborhood of 30c per lb. and we believe that base size E. B. B. galvanized steel wire is over 6.0c. per lb., so that roughly, copper would cost about five times that of steel rather than ten times. Undoubtedly some of the steel men present can comment on these figures.

Mr. Dwight has very naturally and properly chosen examples in which cases the use of steel would be more advisable and has very clearly shown in certain cases that it is worthy of careful consideration. It would, however, be unwise to consider that its use is of general application and in working out specific problems we must in all cases put both metals on an equal footing, standing strictly on their relative merits, commercial costs, and consequent applicability. In other words the question is purely an economic one, and in the vast majority of cases, copper will undoubtedly be found the least expensive, all things considered.

Mr. Dwight has made an excellent presentation of this subject and it is worthy of very careful thought.

T. H. Worcester: Mr. Dwight's paper gives valuable additional data on the subject of iron and steel electrical conductors and will be of considerable assistance to engineers in designing circuits in which such conductors may be used. The data which have previously been available are so scattered and meagre that it has been difficult to find information on a chosen size and quality iron wire or even to interpolate between known values on given sizes and qualities. With the help of Mr. Dwight's data this will be much simplified, since he has given information covering a wide range in sizes of wires, in current densities and in methods of spiraling. It is unfortunate that a greater range in quality of material is not covered and moreover that the principal quality considered is not a duplicate of American product so that direct comparisons might be made. Tests on effective resistance which we have made on ¼-in., ⅜-in. and ½-in. seven strand steel of the Siemens-Martin grade correspond very closely to the results shown in Figures 3 and 6. Our tests were not made with as high current values as those shown by Mr. Dwight, so that the drooping characteristics of the upper end of the curves has not been checked. However, this droop in the curves is what one would expect after the iron reaches saturation and the general character of the curves has been checked on other grades and sizes of wire.

As regards the internal reactance of iron cables, the value of 75 per cent of the a-c. resistance for corresponding currents seems to be high except for conductors having diameters greater than ½-inch or those made of iron having relatively high permeability. The tests mentioned above on steel wire show the reactance to be about 30 per cent of the resistance for ¼-in. and ⅜-in. cables and 50 per cent for ½-in. cable. However, this is subject to such variation with permeability and current density that it is very desirable to test samples of the conductor which it is proposed to use if accurate values are desired.

One of the interesting points about iron wire conductors is that the purer and more costly grades of wire have higher effective resistance and reactance on a-c. than the cheaper grades of steel wire, even though the latter have higher resistance on direct-current. In considering this point, however, it must not be forgotten that the high grade iron wire will not deteriorate as rapidly as steel wire after the galvanizing is once scaled off and that in some cases it may be more economical.

The advantage of using many small wires stranded together with reverse spiral in alternate ropes is worthy of careful consideration. From a theoretical electrical standpoint such cable is to be preferred. In practise, however, finely stranded cable may prove troublesome from breakage of the wires either by rusting through or by short-circuit arcs. Furthermore, finely stranded cable when each wire is galvanized as it should be, is considerably more costly than coarsely stranded wire. For the larger sized cables—½-in. and above—the 7 x 7 strand is permissible, but for the smaller sizes its use is questionable.

In view of the fact that there will be a continual demand for steel conductors in the future it is very desirable that more complete data be obtained on American grades at as early a date as possible.

David B. Rushmore: A subject of this kind is always of interest, because of changing conditions, and with the present prices of copper and aluminum, and because of the price today for steel and iron, which will probably be reduced before the others are, there will undoubtedly be, from a purely economic standpoint, a certain field for the use of steel conductors. That these have been used, and are being used, to some extent, has been mentioned in the paper—in small installations, often where the western lines run out a very small line at high voltage to a prospect—a mine may be developed later, but they are not quite sure, and the man himself just wants a little power for drilling and hoisting. Nobody knows what the future condition is going to be, so that the minimum of installation expense is usually the first consideration, and the efficiency is not of the first importance.

There are some very interesting points in regard to the deterioration of iron and steel under weather conditions. Those of you who have visited the Panama Canal will remember there is a lot of old French machinery, made in Belgium, which is still around there in heaps, or was a few years ago when I was there, and not rusted at all, with no sign of deterioration on it. Having occasion to look this matter up, to see what it was, I found that it is puddled iron, wrought-iron, and the apparent reason is that the little grains or globules of iron are covered by silicate flux which prevents the oxidation of them. As is known, a wrought-iron roof will stand practically indefinitely without rusting. Whether that is a metal which could be used as a conductor or not, I am not sure.

There is an interesting phase about the use of iron and steel conductors, in the rather able presentation of the paper and the discussion which has been had and has covered most of the points, that has not been mentioned, and that is its protective action against high-frequency disturbance. A patent has been taken out by an Italian engineer for covering copper-clad conductors with a nickel covering of high resistance so that the action of the high-frequency current in what is known as skin effect, forcing the conductor to the outside of the duct, forcing it into a cylinder of very high resistance, which absorbs the energy of surge and prevents it from passing along the line. Some such effect as that would be brought about in high-frequency disturbances which would have to stay in or on the steel, and which would be absorbed more readily than in a conductor of lower specific resistance.

It is apparent that later on this sub-division of conductors in cables, is highly desirable, and the great pressure now being put forth for the use of higher voltages—there are quite a number of active propositions at present for 200,000 volts—is forcing the conductor up to the limit of corona, so that the size of the conductor is determined much more by corona than by the current capacity, and the size of the conductor will, for small lines, be quite independent of the load transmitted. So, in many special cases, the steel conductors can be considered at the present time, and as has been said, it is a subject which is worthy of careful scientific investigation and of much more careful commercial study.

S. C. Coey: I had one question I would like to ask Mr. Dwight on the curve Fig. 1. I wonder if he has any explanation to offer as to why the curve for the smaller sized wire should have a higher peak than for the larger sizes. It apparently is while the iron or steel is becoming saturated and it would seem to me you would have about the same for different sizes.

W. T. Snyder: It occurred to me in connection with the use of steel wire there would necessarily be connections and some of the taps made with copper wire, small copper feeders branching off. I wonder what the electrolytic effect would be there, what chemical action would take place, if that would result in any undue harm. I understand that in the case of the use of copper-clad steel, if the copper envelope is scratched, and the steel is exposed, that chemical action is set up between the two elements and it rapidly destroys the wire. I wonder if the same effect would take place at the tapping of a copper wire onto a steel wire. Also, in the case of tapping of a steel wire onto another steel wire, what is the method of splicing to prevent holding water and bringing about rapid corrosion.

David B. Rushmore: It might be possible that some one here would be able to suggest a solution to a point which has not up to date been forthcoming. There have been put into use, in the past few years, a number of transmission lines of copper stranded cable with hemp centers. This, in general, has been very disastrous. In the case of one line, which was put in in South America, a cable after a period of a year or two went all to pieces. There was some action which took place between the hemp center and the copper adjacent to it which corroded the copper badly and there was evidently a chemical action which penetrated the copper for about one-quarter of the diameter.

I saw sections of the cable which were sent north, and in all our efforts we were never able to get a satisfactory explanation as to what the cause of the trouble was. The use of such copper cable, with hemp centers, has, so far as I know, been almost entirely discontinued.

The longest practical transmission line I know of, is one feeding into Los Angeles, from a point about 250 miles distant to the north, a line of the Pacific Light & Power Company, which is operating at 150,000 volts, and it is interesting to learn that they are having very little operating trouble with it. The cable there consists of a steel center, both for strength and to increase the diameter of the conductor, with stranded aluminum around and outside, and there was considerable discussion just on the point brought out, whether there might not be, as the effect of rains and moisture saturating the cable, electrolytic action which would tend to destroy it. The practical result of that would probably appear within a year or two, but there is no evidence up to date to show what it will be. Why the cable with the hemp center and copper conductors should have gone to pieces as it did, the copper becoming extremely brittle and cracking at right angles to the length of the wire, has never, so far as I know, been explained.

H. B. Dwight: In reply to the question why some of the curves in the paper have sharper peaks than others, I believe this is merely accidental, depending on the relative magnitude of the scales to which the curves were plotted.

Regarding the electrolytic action at a joint between a steel cable and a copper cable, it may be necessary to protect such joints from the weather, but the action is not to be considered as an objection to the use of steel cables. In the descriptions of practical operation referred to in the paper, it was stated that this trouble was feared, but that no trouble was experienced.

Mr. Doane's discussion was very interesting and has added considerably to the complete description of the standing of steel conductors in commercial work at the present time. The steel conductors used at present are undoubtedly a small percentage of the copper conductors used, but this ratio may be changed by the high price of copper and by an increase in the knowledge of the alternating-current properties of commercial steel cables.

Mr. Doane stated that the ratio of cost of copper to steel should not be 10 to 1 as given in the paper, but should be 5 to 1 as shown by the price of "extra best" iron wire. It is pointed out in the paper that according to the tests published in Germany and also tests made by the Bureau of Standards, pure iron is not the best for alternating-current work, and there is good hope that the grade of steel most suitable for power lines will cost only one-tenth as much as copper.

With reference to the statement that there are only a half dozen lines in America where corona loss is important, it is evident that a pressure of 150,000 volts is referred to, but it is easy to show that corona is of importance at the very common pressure of 100,000 volts. Two values of corona limit of voltage are given in the paper, namely, 85,000 volts for No. 1 copper and 76,000 volts for No. 2 copper at a usual spacing. Although such small conductors are sometimes used on 100,000-volt lines, the practise is probably not economical or advisable, owing to the heavy corona losses in bad weather. Accordingly, on branch lines of 100,000-volt systems, there is an opportunity for the use of steel cables which would have lower conductivity and cost than No. 1 copper, but would have larger diameter and would be free from corona loss.

Mr. Worcester in his discussion emphasized the value of curves similar to those in the paper, but applying to American steel cables. I believe that in view of the small cost of making the tests, it is proper to urge that test curves be prepared and published, of several grades of American commercial steel cables of medium strength and cost.

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ELECTRICAL MACHINERY TESTS AND SPECIFICATIONS BASED ON MODERN STANDARDS

BY H. M. HOBART

Abstract of Paper

Comparisons are made of the standardization rules for electrical machinery now in force in various countries. It is shown that the differences are of a very minor character and that machinery built in conformance with the American rules will usually also conform with the rules employed in other countries. The suggestion is made that 55 degrees could be employed as the ambient temperature of reference for tropical ratings and it is maintained that such a plan fits in nicely with the value of 40 degrees already adopted as the ambient temperature of reference for other than tropical ratings. Attention is called to a series of acceptance tests on some large waterwheel generators and to the temperature results obtained by making cyclic heat runs on these machines.

IN THE course of his work the author frequently has been brought face to face with the fact that the mere drafting and circulating of standardization rules constituting a radical departure from former practise, are insufficient to bring about general use of the contemplated modifications. It is necessary to have a wide and thorough discussion in order that there shall be a clear appreciation of the reasons for and the consequences of the alterations. Furthermore, in working out so comprehensive a proposition as that represented by the Standardization Rules of the American Institute of Electrical Engineers, provision has to be made for a large number of details, whose importance, if not especially emphasized, is liable to be overlooked in the practical application of the rules to concrete cases. There are a good many sections in the rules, which at first glance would seem of minor importance, but which, nevertheless, set forth requirements which cannot be disregarded advisedly on the occasions of acceptance tests and in the drafting of specifications.

The author recently has had occasion to carry out a series of very interesting acceptance tests upon some large waterwheel-driven generators. Since it was the purpose to make the tests with exceptional care, it seemed to be an admirable occasion to subject the American rules to a thorough test. Consequently especial endeavors were made to conform with the requirements set forth in the American rules. Various points arose in which this practical process of putting the rules to the test, suggested the desirability of slight modifications to increase their definiteness.

In the original drafting of a specification, the feasibility of determining by simple tests that the requirements of the specification have been fulfilled, should always be kept prominently in mind. Indeed the close association between a consideration of the terms of the specification and a consideration of the general subject of the carrying out of acceptance tests is so obvious that it is unnecessary to further justify the predominance given in this paper to the acceptance-tests aspects of the subject.

As regards electrical machinery, the British Standardization Rules issued by The Engineering Standards Committee in Report No. 72 and the October, 1916 edition of the Standardization Rules of the American Institute of Electrical Engineers are in such close agreement that machinery built and rated to conform with the one set of rules will usually also conform with the other set of rules. The slight quantitative differences between the two sets of rules practically always will be covered by the margin reserved by manufacturers. This general statement of fact is made as a matter of interest, but of course it is always important to make certain that the standardization rules according to which the machinery is specified in any particular case agree in all particulars. An appendix to this paper contains in tabular form a statement showing the slight differences in the temperature limits in the British and American standardization rules. The heating and temperature sections of the 1916 edition of the Italian rules are also in close agreement with the corresponding sections of the British and American rules.[1]

The British rules do not yet cover quite as many subjects as the American and Italian rules, which already contain sections relating to efficiency and to regulation in addition to those covered by all three sets of rules. The limitations of this paper will not permit of a discussion of these two latter subjects nor of the subject of dielectric tests, notwithstanding their interest and importance. The paper is further limited chiefly to points relating to rotating machinery, the important subject of stationary transformers being excluded since its consideration would have too greatly increased the length of the paper.

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[1] "Standards for the Ordering and Acceptance of Electrical Machines" issued by the Italian Electrotechnical Association; Central Offices: 10 Via S. Paolo, Milan.

TEMPERATURE STANDARDS

So far as relates to heating and temperature, the plan underlying all modern standardization rules for electrical machinery consists in establishing approved upper limits of temperature. These limits are such as to permit of continuous subjection thereto. While as an actual fact these limiting temperatures could be exceeded safely for short intervals, this is not permitted by the rules. The approved upper limits have been determined upon with a view to providing adequate factors of safety. Having determined upon approved values for the upper temperature limits, the next step consists in adopting a reference value for the ambient temperature. The difference between the approved upper limits and the ambient temperature of reference constitutes the limiting temperature rise. The *rating* is obviously a function of the thus-deduced temperature rise.

AMBIENT TEMPERATURE OF REFERENCE

In the British, the American and the Italian rules the ambient temperature of reference is 40 deg.[2] This value is adopted because it is a temperature approached in all parts of the temperate zone at some time during the year.

In none of these three sets of rules is there, as yet, any provision for machinery for tropical countries. The author would suggest 55 deg. as a suitable ambient temperature of reference for tropical ratings. The suggestion is not based on any contention that electrical machinery is liable to be installed in locations where an ambient temperature of 55 deg. would be at all likely to occur, but for the three following reasons:

First, that it is desirable to employ a value which will ensure a margin of a few degrees; *second*, that the ambient temperature of reference for tropical ratings should not exceed that for temperate ratings by less than 15 deg. (a less difference would lead to ratings which would be so nearly the same for the two cases that the difference hardly would be worth taking into account); *third*, that the value of 40 deg. is, strictly speaking, rather too low for the temperate zone. While its occurrence is by no means usual, it is so often approached within a few degrees that it cannot be said to provide much margin when employed as a standard reference value. Since 40 deg. is now firmly established for the temperate zone, the consistent value for a basis for tropical ratings is 55 deg. Practical experience has demonstrated the importance of employing distinctly lower ratings for electrical machinery destined for use in tropical countries, than ratings which have proven satisfactory for the temperate zone.

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[2] Throughout the paper, all temperatures are given in the centigrade scale.

The ambient temperature of reference of 40 deg. for all countries in the temperate zone was adopted only after very careful investigations. While there are many localities where an outdoor shade temperature of 40 deg. is never attained at any time in the year, nevertheless there are in the temperate zone very few localities where an outdoor shade temperature of 35 deg. is not sometimes closely approached. It was decided that 35 deg. did not afford sufficient margin. The following data bear out the correctness of this decision.

From the report of the chief of the Weather Bureau have been taken the following maximum temperatures recorded in any station in the designated states during the year 1908.

42 deg.	Kansas, Nebraska, New Mexico, Oklahoma
43 "	Montana, Idaho, Oregon, South Dakota, Utah, Wyoming
44 "	Washington
46 "	Texas
47 "	Nevada
49 "	California
52 "	Arizona

In America, meteorological observations are often made by amateur volunteers and it is possible that some of these higher values may not have been adequately verified.

From "Symons Meteorological Magazine" for 1912 has been compiled the table on the following page, of temperatures at 20 places in the British Empire. The records consulted were compiled from 30 places in the British Empire. For the remaining ten places 32.5 deg. was not reached at any time during the year 1911.

It is of importance to emphasize that it is not essential to be able to reconcile the ambient temperature of reference with the maximum temperature occurring in the locality where the machinery is to operate. The greater the amount by which the ambient temperature of reference exceeds the temperature where the machinery is operated, the greater is the factor of safety. The shade temperatures set forth in meteorological records are usually taken where there is no local source of generation of heat and where air circulates freely. Electrical machinery in operation *itself* constitutes a source of heat and increases the temperature of the surrounding air. Furthermore electrical machinery is often located in places where the circulation of air is very much restricted. Consequently the ambient temperatures near electrical machinery will generally considerably exceed the shade temperatures recorded by meteorological stations. Indeed there is no proof that the actual ambient temperatures in the neighborhood of electrical machinery are related at all closely to the official temperatures issued from meteorological stations. It is evident from the tables which have been given that, strictly speaking, even 40 deg. is too low for the reference temperature, on the basis that it is to be a value that shall *never* be even *slightly* exceeded. The reference value adopted must rest upon an assumption and it is important that the assumption shall be conservative. In the rules of the Verband Deutscher Elektrotechniker the ambient temperature of reference is 35 deg. The precise statement in this respect as set forth in the V. D. E. rules is as follows:

NUMBER OF MONTHS DURING 1911 IN WHICH THE MAXIMUM SHADE TEMPERATURE EQUALLED OR EXCEEDED:

	32.5 deg.	35 deg.	37.5 deg.	40 deg.
London	3	1	0	0
Malta	1	0	0	0
Lagos	4	0	0	0
Cape Town	3	3	1	0
Durban (Natal)	3	1	0	0
Calcutta	9	4	2	0
Bombay	9	0	0	0
Madras	8	8	6	3
Colombo (Ceylon)	4	0	0	0
Hongkong	3	0	0	0
Sidney	3	2	2	0
Melbourne	4	3	3	2
Adelaide	6	6	5	2
Perth	4	4	3	2
Coolgardie	6	6	6	5
Hobart (Tasmania)	2	2	1	0
Jamaica (Kingston)	9	3	0	0
Toronto	1	0	0	0
Fredericton	1	1	0	0
Blömfontein	5	2	0	0

"It is assumed that the temperature of the surrounding air will not exceed 35 deg."

In the British, American and Italian rules, it is assumed that the temperature of the surrounding air will not exceed 40 degs. It is probable that in the neighborhood of electrical machinery, *i. e.*, at a distance of 1 to 2 meters from the machine, as set forth in Section 314 of the American rules), the temperature of the air at some time during the year exceeds 35 deg. in the majority of cases and there is often a considerable probability that the ambient temperature near electrical machinery will occasionally rise a few degrees above 40 deg. But by the adoption of 40 deg. as the ambient temperature of reference there will for almost all installations of electrical machinery in the temperate zone probably be a margin of a few degrees during 99 per cent of the year. For such an indefinite state of affairs, it is reasonable to adopt a value which offers some probability that there will be such a margin. It is not possible to predict the maximum ambient temperature in the neighborhood of an electrical machine within several degrees even when the machine is not running, and the value to which the ambient temperature is likely to attain when the machine is in operation is still more indefinite. The records of the official shade temperature for any given locality are of little or no service. Indeed the temperatures maintained within buildings are apt to be fully as high in cold climates as in warm climates. In view of the indefiniteness inherent to the subject, and of the importance of taking a conservative value, it would appear that the reference value of 40 deg. for the ambient temperature in regions in temperate climates is certainly not too high and reasonably might be criticized as too low. From whatever way the matter is approached there is obviously a 5-degree-greater factor of safety, (in other words, a more conservatively rated machine), when the rating is based on an ambient temperature of reference of 40 deg., as in the British, Italian and American rules, than by basing it on 35 deg.

A distinct commercial value attaches to the provision of means for maintaining at a reasonably low temperature the premises in which electrical machinery is operated. If a temperature of 30 deg. on these premises is never exceeded at any time during the year, then the maximum temperature ever occasioned in the electrical machinery when operating at its rated load is 10 deg. below the approved limits and the margin of safety is very much greater.

THE AMBIENT TEMPERATURE DURING ACCEPTANCE TESTS

In determining the ambient temperature on the occasion of acceptance tests in the case of rotating machines cooled by forced draft, it is provided in Section 311 of the American rules that "a conventional weighted mean should be employed, a weight of *four* being given to the temperature of the circulating air supplied through ducts and a weight of *one* to the surrounding room air." Thus, for example, if, on the occasion of an acceptance test, the circulating air is taken from outside the building and has a temperature of 14.0 deg. at the intake of the machine, while the temperature of the air in the room is 24.0 deg., the ambient temperature, from which the temperature rise is determined, should be taken as:

$$\frac{4 \times 14.0 + 1 \times 24.0}{5} = 16.0 \text{ deg.}$$

If the temperature of the machine at the end of the heat run is 70 deg., then we have:

Temperature rise *in accordance with the American rules*
$= 70 - 16 = 54$ deg.

Temperature rise *above room temperature*
$= 70 - 24 = 46$ deg.

Temperature rise *above inlet temperature*
$= 70 - 14 = 56$ deg.

While, strictly speaking, the weights given for the two air temperatures should depend upon the characteristics of the particular machine under test, the correction is of such moderate amount that it has been desirable in the interests of simplicity and definiteness to standardize the weighting of the two temperatures.

It is further to be noted (from Sections 314 and 315) that the room temperature is to be taken as the mean of "several thermometers placed at different points around and half way up the machine, at a distance of one to two meters," and that the value to be employed shall be the mean of the readings of these thermometers taken at equal intervals of time during the last quarter of the duration of the test.

The temperature of a large machine will not at all promptly follow the changes which are always taking place in the temperature of the premises where a heat run is being made. Consequently, if no appropriate provision be made, a greater temperature rise will usually be recorded if the heat run concludes shortly after midnight, when the air temperature in a large factory building is usually falling, than if the heat run is concluded in the middle of the forenoon, when the air temperature of such a building is usually rising. Errors from this source are decreased by complying with the requirement in Section 316 that "the thermometer for determining the ambient temperature shall be immersed in a suitable liquid, such as oil, in a suitable heavy metal cup." With a falling room temperature, a mercury thermometer exposed to the room air might read at least a couple of degrees lower than an identical thermometer with its bulb immersed in oil in one of these metal cups.

To those who have not had extensive experience in testing large generators, these various precautions may seem trivial. As a matter of fact they ensure immunity from errors which may easily amount to several degrees difference in the result obtained for the temperature rise.

The British, Italian and American rules are now in agreement in providing that for rotating machinery no correction is to be made in the temperature rise on account of the particular value of the ambient temperature on the occasion of the test. The British and American rules simply suggest, (Section 320 of the American rules), that "tests should be conducted at ambient temperatures not lower than 15 deg." The corresponding Italian rule is as follows:

> "For ambient temperatures lower than 40 deg. during the tests, no correction shall be applied to the results of the measurements so long as the temperature does not fall below 10 deg.; however it is not convenient that tests should be carried out at temperatures below 10 deg."

This plan of omitting any corrections is a decided improvement over the old plan of applying to the observed temperature rise, a correction which was a function of the ambient temperature at the time of the test. Careful tests have shown that the temperature rise of the average machine is not very dependent upon the temperature at the time of the test and that the reliability of the result cannot be increased by means of any simple corrections. Elaborate tests have been made with the object of clearing up this matter by making heat runs in a room maintained successively at low and high temperatures. The rise with low room temperatures averaged as great as the rise with high room temperatures, the inverse change in core and copper loss with change in temperature combined with the very rapid increase in radiation at high temperatures tending to render the result independent of the room temperature.

Another progressive ruling which is identical in the British and American rules is that relating to the duration of heat runs. It is to the effect that:

> "The temperature test shall be continued until sufficient evidence is available to show that the maximum temperature and temperature rise would not exceed the requirements of the rules, if the test were prolonged until a steady final temperature were reached."

For conditions where the temperature of a part cannot be obtained until the machine is shut down, (for example, the resistance of the stator windings of a polyphase generator), the rules make the following provision:

> "Whenever a sufficient time has elapsed between the instant of shut-down and the time of the final temperature measurement, to permit the temperature to fall, suitable corrections shall be applied, so as to obtain as nearly as practicable the temperature at the instant of shut-down. This can sometimes be approximately effected by plotting a curve, with temperature readings as ordinates and time as abscissas, and extrapolating back to the instant of shut-down. In other instances, acceptable correction factors can be applied."

As to these *acceptable correction factors*, it may be said that from the many test results available on the records of manufacturers, it will be known generally that, for a particular type of machine, the cooling of the hottest-spot will be approximately at some particular rate per minute for the average of the first three or four minutes after shut-down. At the time of the acceptance tests, both parties to the transaction usually will readily arrive at a satisfactory agreement that for any particular machine under test a certain number of degrees shall be added to the temperature determined by resistance measurements made within a given number of minutes of shut-down. It rarely would be worth while to encumber the specifications and guarantees with a clause setting forth the amount of this correction, but it is simple enough to do so when it is considered that it is of sufficient consequence to have the amount definitely stipulated.

EMBEDDED TEMPERATURE DETECTORS

The American rules (Section 355) require that for the purposes of acceptance tests, the temperatures of the stators of large generators shall be determined by means of embedded temperature detectors, several of which shall be employed. These are to be so located as to disclose as nearly as possible the temperature of the hottest spot existing anywhere in the machine. These embedded temperature detectors consist of thermocouples or resistance coils. An extensively employed design of embedded temperature detector of the resistance type, has a length of about 10 in. (25.4 cm.), and, at a temperature of 25 deg., its resistance is just 10 ohms. In Fig. 1 are shown sections through slots for two types of slot windings usually respectively designated two-layer and single-layer windings. It is required in Sections 353 and 354 of the American rules that "a liberal number" of temperature detectors shall be placed in the locations designated in Fig. 1 as *A* and *B*, for two-layer windings, and *B* and *C* for one-layer windings.

THE HOTTEST-SPOT TEMPERATURE

The rules stipulate that for machines with two-layer windings, the hottest-spot temperature shall be considered to be 5 deg. greater than the highest reading obtained by any of the embedded temperature detectors; and that in single-layer windings the hottest-spot temperature shall be that obtained by adding to the highest reading 10 deg., plus 1 deg. per 1000 volts above 5000 volts of terminal pressure.

These corrections are brought together in the following table:

For two-layer windings.	Add 5 degrees to the highest reading.
For single-layer windings for 5000 volts or less.	Add 10 degrees to the highest reading.
For single-layer windings for more than 5000 volts.	Add to the highest reading 10 deg., plus 1 deg. for every kilovolt by which the voltage between the terminals of the machine exceeds 5 kv.

Thus for a three-phase machine with an 11,000-volt single-layer winding, the correction to be added to the maximum observable temperature in estimating the hottest-spot temperature, is 16 deg.

Usually the hottest-spot results derived from the indications of the embedded temperature detectors are the most satisfactory. It is, however, quite possible that the temperature rise derived from measurements of the resistance of the stator windings at the conclusion of the heat runs sometimes may be greater than the temperature rise determined from the embedded detectors. Consequently it is provided in Section 352 of the American rules that when the embedded-detector method is used, the results shall, *when required*, be checked by the results obtained from measurements of the resistance of the stator windings, and "the hottest spot shall then be taken to be the highest value by either method, the required correction factors being applied in each case." By correction factor is meant the number of degrees which shall be added to the observed temperature to obtain the hottest-spot temperature. For the resistance method the correction factor is 10 deg.

As regards the so-called correction factors[3] established in the American rules, it would appear that the hottest-spot temperature determined by adding to the observable temperature the *stipulated* correction factor shall constitute the criterion and that a machine could not be rejected on the ground that other evidence demonstrated that a still-greater temperature existed at some point of the winding. For example, for purely research purposes it would be practicable to locate temperature detectors actually against the copper of a high-pressure winding. In some special cases such temperature detectors might disclose temperatures exceeding those obtained by adding the conventional correction factors to the observable temperatures. Since the conventional correction factors have been established with every intention that they shall be liberal and since definiteness in contracts is essential, the hottest-spot temperatures obtained by complying with the methods approved in the American rules should be taken as final, irrespective of evidence of the existence of higher temperatures. It is believed that it would be only in exceedingly rare instances that higher temperatures could be

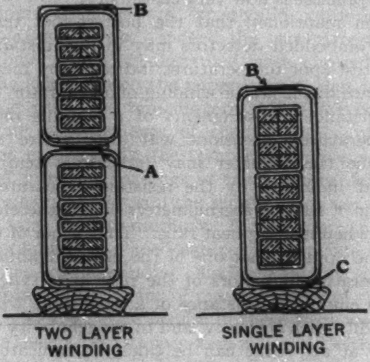

FIG. 1

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[3] These are not factors. Some better designation should be substituted.

found and that they would exceed the conventional hottest-spot temperatures by immaterial amounts. However, in so far as the rules on this point may be obscure in the least, it would seem to be very important to make their intention unmistakably evident.

The use of embedded temperature detectors has been demonstrated to be of great advantage. When only required for the acceptance tests the leads from the detectors may, at the conclusion of the tests, be cut off, and the detectors abandoned. But it is of decided advantage, in the service operation of large generators, to be able, at any time, to ascertain the internal temperatures from the direct readings of switchboard instruments. This practise is now very customary.

It has been mentioned that the hottest-spot temperatures indicated by embedded detectors may in rare instances be less than the hottest-spot temperatures indicated by measurements of the resistance of the stator winding of a generator. Moreover since the resistance measurements of a winding only disclose *average* temperatures, occasions will arise where a suitably-located surface thermometer may indicate a temperature in excess of that indicated by the resistance measurements. A liberal number of surface thermometers ought, therefore, also to be employed when making heat runs. The author of the present paper is of the opinion that one of the chief advantages of embedded temperature detectors of the resistance type relates to the ability to employ a resistance of a magnitude which can be measured readily with accuracy, and to the reliability with which its resistance at any time can be taken to indicate a definite temperature. The temperature rise obtained from the increase in the resistance of an armature or field winding would be of distinctly greater value were it practicable to know accurately the temperature of the winding on the occasion of the measurement of the cold resistance. It is rarely practicable to incur the delay before commencing a heat run, which would be necessary to ensure that an armature or field winding is within a couple of degrees of the surrounding temperature. Often when it is assumed that the winding's temperature is substantially identical with that of the surrounding air, there is actually a difference of over five degrees and consequently the measured cold resistance is associated with a temperature over five degrees different from its actual temperature and a corresponding error is incurred in deducing from its hot resistance the temperature of the winding at the end of the heat run.

Some such plan as that set forth in the following clause, if the conditions of practise should permit of its adoption, would provide a way out of the difficulty and much increase the value of temperature determinations by measurements of the resistance of the main windings:

> "In order to avoid protracted delays in the testing of a machine, in bringing the temperature of its windings into accord with the ambient temperature, the resistance of the windings of a machine, reduced to 40 deg., should be made a matter of factory record for all machines subject to temperature measurement by resistance under these rules."

In general, the author's opinion in this matter is that the methods of obtaining temperatures by surface thermometers and by measurements of the resistances of the main windings should not be discarded in favor of the newer method by embedded temperature detectors, but should continue to be employed *in addition thereto*. Indeed the careful tests made on a large machine, which are described later, showed, as may be seen from the last Table in the paper proper, that in two out of the three heat runs, the temperature rise *of the hottest spot* as deduced from measurements of the resistance of the stator windings was greater than the temperature rise *of the hottest spot* deduced from the readings of temperature detectors, and that in the remaining heat run the temperature rise *of the hottest spot* was the same by both methods. Furthermore the readings of mercury thermometers placed against appropriate parts of the surface of the rotor winding disclosed higher temperatures than were obtained by means of measurements of the resistance of the rotor winding. The results in these tests were especially reliable since the cold resistances were measured with the greatest care after the machine had been standing idle for two days, so that its windings at the time of measuring their resistances before beginning the heat run, should be at the same temperature as the surrounding air.

A recommendation to take advantage of all three methods, that is to say, Method I, surface thermometers, Method II, main-winding resistance measurements, and Method III, embedded detectors, might at first sight be condemned as impracticable on all except large, valuable machines, on the ground that the expense of making such thorough tests would be prohibitive. Were it necessary to make these measurements on each and every machine, such a criticism would be well founded. But the author of this paper holds the opinion which, in another publication, he has expressed as follows:

"Although the rules contain no explicit statement to that effect, it may doubtless be understood that it is not intended that a test by the prescribed method need necessarily be made upon every individual machine comprised in a transaction. The simplest method, as above explained, is usually Method I, and in the interest of avoiding needless expense, it should often be practicable to arrange for a judicious employment of Method I for most of the machines of a given size, employing Method II or III, as the case may be, on a few of the machines, and thereby arriving at a factor by which the results obtained by Method I require to be multiplied in order to arrive at the results which *would have been obtained* on those particular machines had Methods II and III been employed. In other words, it should not be concluded that the less simple measurements will necessarily be made on every machine, but rather that conclusive evidence shall be provided to insure that *had the measurements been made*, the temperature would have been within the required limits."

Further Consideration of the Hottest-Spot Temperature. The American rules lay emphasis on the hottest-spot temperature. Limiting approved values for the hottest-spot temperatures are set forth. The limiting values depend chiefly upon the class of insulating material employed. Insulating materials are divided into three classes, *A*, *B*, and *C*. These classes are defined as follows in the American and British rules:

Class of insulation	Description of insulating material
A	Cotton, silk, paper and similar materials when so treated or impregnated as to increase the thermal limit, or material permanently immersed in oil; also enamelled wire*
B	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A material or binder is used for structural purposes only, and may be destroyed without impairing† the insulating or mechanical qualities of the insulation.
C	Fireproof and refractory materials, such as pure mica, porcelain, quartz, etc.

*For cotton, silk, paper and similar material, when *not* treated, impregnated or immersed in oil, the highest temperatures shall be 10 deg. lower than the limits given above for Class A.

†The word impair is here used in the sense of causing any change which would disqualify the insulation for continuous service.

No limit is placed upon the temperature of Class C insulation. The permissible temperatures and temperature rises of electrical machinery at present are based chiefly upon the characteristics of Class A and Class B insulations. The British and American rules agree in adopting 105 deg. and 125 deg. for the limiting hottest-spot temperatures for these two classes of insulations. The author believes that it may be of some interest for him to state that he shares with many other engineers, the opinion, based on extensive tests, that 105 deg. for Class A insulations and 150 deg. for Class B insulations are both thoroughly conservative limits, when all the designing and manufacturing processes are carried out with due regard for numerous important details. But, failing the availability and application of skill and experience, even much lower temperature limits for Class A and Class B insulations will not ensure a satisfactory product. It is difficult to see how any Standardization rules can afford the necessary assurance in this respect. The successful withstanding of acceptance tests does not necessarily constitute evidence that the insulations will endure the stipulated temperatures (and other deteriorating influences which vary from instance to instance), for a satisfactory term of years. Fortunately the manufacturer's interest in the success and reputation of his product usually affords the required assurance. Indeed there is usually a strong tendency on the part of the manufacturer to refrain from taking advantage of temperature limits of established practicability until years of study by tests on samples and on experimental machines have established beyond all reasonable doubt the appropriateness of the higher limits. It is, however, important to the industry to take advantage of higher limiting temperatures as soon as a reasonable amount of experience is gained, since this permits of reduced capital costs for machinery and rarely affects prejudicially the working costs except where the action is premature. The adoption of new limits by bodies of the standing of the British and American Standards Committees is ample proof that the evidence in the case has been carefully sifted and that the time is ripe for the modification. While the temperature limits for Class A and Class B insulations can both be safely exceeded for short periods, it is in the interests of reserving reasonable factors of safety to establish them (as is expressly emphasized in the British and American rules) as limits which shall *never* be exceeded. In the British and American rules the limit at present standardized for Class B insulations is 125 deg. but there is a well-developed opinion in America that since there is now a great deal of experience on which to base the action, the limit for Class B insulations could with advantage be raised to 150 deg.

INTENSIFIED AGING OF INSULATIONS

Reference has been made to the impossibility of framing rules to ensure that the insulations employed have satisfactory longevity. Naturally, however, the aging of insulating materials is a matter of great importance to the manufacturer. The author has been much interested in some elaborate series of tests of this character. The point of most importance to decide is that of the temperature which can be withstood for 10 to 20 years by an insulating material. It might be supposed that subjection to super-temperatures for brief periods would permit of forming an opinion regarding the life corresponding to lower temperatures. To a certain extent brief tests for short periods at super-temperatures are useful but conclusions drawn therefrom must, at the present state of affairs, be regarded as only of the nature of very rough evidence. For some Class A insulations, values of the order shown in the following table are indicated:

Temperatures which can be withstood successfully, not only electrically but physically by approved Class A insulations:

For seconds	250 degrees
" minutes	200 "
" hours	170 "
" days	150 "
" weeks	130 "
" months	115 "
" years	105 "

A very slight modification in the composition or construction of the insulation, however, might completely disqualify it for withstanding any considerable super-temperatures, even for brief periods. Tests on various approved Class B insulations lead to values which, while quantitatively higher by a matter of some 50 deg., are qualitatively very similar.

Reasonable factors of safety must, however, be reserved. This is realized by the British, American and German Standards Committees and no recognition whatsoever is extended to the ability of insulations to successfully withstand super-temperatures for brief periods. Thus in the American rules we have Section 305 A, to the following effect:

Section 305 A. Whatever may be the ambient temperature when the machine is in service, the limits of the maximum observable temperature and of temperature rise specified in the rules should not be exceeded in service; for, if the maximum temperature be exceeded, the insulation may be endangered, and if the rise be exceeded, the excess load may lead to injury, by exceeding limits other than those of temperature; such as commutation, stalling load and mechanical strength. For similar reasons, load in excess of the rating should not be taken from a machine.

It is thus clear that in the interest of securing a liberal margin of safety we must forego rigorously the temptation to expose the insulation of machinery, even for brief periods, to temperatures in excess of the limits approved in the American rules.

This practise is in striking contrast to that underlying the older Standardization rules which authorized higher temperatures for short periods. Probably the credit for the modern departure belongs to the German Standards Committee, which, for some years, has employed the plan of permitting overloads with the same temperature limits as for the rated load. The following clauses are from the German standardization rules:

Overloading. With the limitation that the overloads only are carried for so short a time, or only occur under such temperature conditions of the machines and transformers that the highest permissible temperatures are not thereby exceeded, machines and transformers must be capable of carrying the following overloads:

Generators Motors Synch. conv. and motor-generators Transformers	25 per cent during one-half hour
Motors Synch. conv. and motor-generators Transformers	40 per cent for 3 minutes

Section 305 A of the American rules, however, contains the restriction that "loads in excess of the rating should not be taken from the machine," lest limits other than those of temperature, such as commutation, stalling load and mechanical strength should be exceeded.

Nevertheless the American rules provide for the case where a machine is required to carry very heavy loads for brief periods. Such a case is met by giving a machine more than one rating. Thus amongst the machinery recently supplied to the Chicago, Milwaukee and St. Paul Railway are some couple of dozen 2000-kw. motor-generator sets for use in substations. These sets have the following three ratings:

Continuous rating....................	2000	kilowatts
Two-hour rating.....................	3000	"
Five-minute rating..................	6000	"

The mechanical strength and the commutating requirements for the five-minute rating are far in excess of those for the continuous rating. But the temperature attained with the continuous rating exceeds that attained with the five-minute rating.

This plan may be employed whenever it is necessary to provide for peaks of load, as in the case, for instance, of crane motors. Knowing the typical duty cycle, we may prescribe a *short-time* rating sufficient to ensure that the motor shall have ample mechanical strength as well as sufficient margin in the matter of commutation, and that it shall not stall with the greatest load which it ever will be called upon to carry. Knowing also the average load, we may prescribe a *continuous* rating which will ensure that approved temperatures shall never be exceeded. Two ratings should suffice, a continuous rating to ensure the non-exceeding of approved temperatures and a short-time rating to ensure the required capacity for the intermittently occurring peaks of load, as regards commutation, stalling load and mechanical strength.

On the whole, while as already stated, we owe the conception of modern ratings to the German Standards Committee, the way in which the American Committee has fitted the conception to the requirements of practise, would appear to be distinctly excellent.

Low-Temperature Circulating Air

For small machines built in large quantities for stock, the ultimate destination is unknown. In normal times a motor driving a printing press in Bombay or Pekin or Moscow is about equally likely to have been built in Berlin or Manchester or Milan or Schenectady. Even if the ultimate destination may be ascertained it is not practicable to countenance departures from the strict letter of the Standardization Rules in the case of small machinery.

But for large machines worth many thousands of dollars apiece and operated under skilled supervision, it would be wasteful to forego any economic advantage compatible with sound engineering practise. As a concrete case let us assume that a large operating company is purchasing a 20,000-kv-a. generator which will be cooled by circulating through it every minute 50,000 cu. ft. (1420 cu. m.) of air taken from outside the building. In the summer, on days when the humidity is high, the circulating air's temperature, even after passing through the air washer, may sometimes be nearly 40 deg. But the nature of the load may be such that the station's peak in summer is half of its mid-winter peak, or even much less. It may be practicable to rely on 15-deg. circulating air for the mid-winter peak. For the limiting temperature for Class A insulation, (105 deg.), this represents 90 deg. "hottest spot" rise as against 65 deg. "hottest spot" rise in the summer. By temperature coils in location A of Fig. 1, the *observable* rises are:

Summer—(105—5—40) = 60 deg.
Winter— (105—5—15) = 85 deg.

Consequently, if the machine has ample margin as regards mechanical strength and if the prime mover is adequate, advantage ought to be taken of its increased capacity in winter which would be of the order of 25 or 30 per cent.

Three such 20,000-kv-a. machines, operated on the basis of loading them up to their capacity as indicated by embedded temperature detectors, would do the work of four machines operated in strict accordance with Section 305 A of the American rules, and the saving in the capital component of the total cost of manufacturing electricity would be quite appreciable.

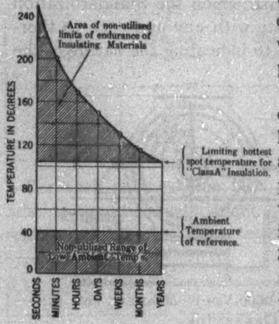

FIG. 2

Such a case would be met by some such clause as follows:

> "Contractors will be required to guarantee that the machine shall be in all respects in strict accordance with the 1916 edition of the American rules with the following exception:
>
> *Exception.* The machine shall have ample mechanical strength and shall be in all other respects adequate to carry the increased load which with a circulating-air temperature of 15 deg., may be carried without occasioning hottest-spot temperatures in excess of those set forth in the American rules as approved for the class of insulation employed. For the acceptance tests, the embedded-temperature-detector method supplemented by measurements of the resistances of the main windings and by surface thermometer measurements, shall be employed for determining the temperature attained.

MARGIN OF SAFETY

Adherence to the recommendations in the British and American Standardization Rules ensure very liberal margins of safety. This is apparent from Fig. 2 in which the shaded areas indicate respectively for machines with Class A insulation, the temperature ranges above the permitted hottest-spot temperature of 105 deg. which technically are available but which are not allowed, and the temperatures below the reference ambient temperature which are liable to exist in most locations during certain seasons of the year. The unshaded area represents the temperature range, utilization of which is approved in the American rules. There is no disposition to suggest encroachment upon these liberal margins of safety; they are simply in accordance with the best and most valued traditions of the engineering profession.

EQUIVALENT TESTS

We now arrive at a matter with which the Standardization Rules do not yet deal, at any rate with any approach to thoroughness. The deficiency relates to indicating the nature of the tests which shall be regarded as satisfactory criteria for determining the temperature rise. Several methods are in vogue, but for testing a single large machine, no method in common use is thoroughly satisfactory. Doubtless the matter will be given very careful consideration by the Standards Committees before rules are adopted.

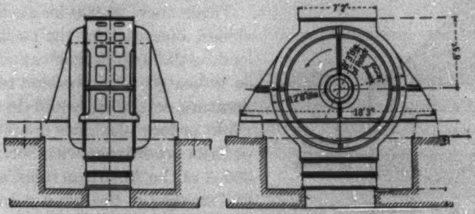

FIG. 3—TWELVE-POLE—8750-KV-A.—6600-VOLT—500-REV. PER MIN.—THREE-PHASE GENERATOR

The author has already mentioned some large waterwheel generators which he recently tested. These were 500-rev. per min., 50-cycle three-phase generators with a rating of 8750 kv-a. These machines were of the design indicated in Fig. 3. Advantage was taken of the opportunity to employ for the heat test a method which may be termed a cyclic heat run.* It appears to

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*This cyclic method of testing electrical machines was first described in an article by Hobart and Punga in the *Electrical World* for April 22, 1905.

See also an article by the author in the *General Electric Review* for November 1911, entitled "A Method for Testing the Heating of Large be especially well adapted to a machine of the kind tested. The test consisted in operating the machine for alternate 15-minute periods on open circuit with super-normal pressure and on short circuit with super-normal current. The degree of the super-normality was so selected as to occasion in each complete half-hour cycle, as nearly as practicable, the conversion into heat of the same amount of energy in each part of the machine as would be occasioned in each part were the machine to deliver the actual load which it was the object of the test to investigate. The normal pressure of the machine was 6600 volts between terminals. (3800 volts per phase) and heat tests were required at each of the three different loads set forth as follows:

Designation of heat run	Kilovolt amperes	Power factor	Current per phase	Terminal pressure
I	7,000	1.00	614 amperes	6600 volts
II	8,750	0.80	766 "	" "
III	10,937	0.80	960 "	" "

For each of the three heat runs it was desired to provide heating conditions equivalent to the loads just set forth. This was accomplished by cyclic tests with the following conditions:

Designation of heat run	I	II	III
For the short-circuit periods			
Rotor excitation (amperes)................	119	148	185
75-deg. rotor $I^2 R$ loss (kw.)...............	5.10	7.9	12.4
Stator current (amperes)................	854	1070	1344
75-deg. stator $I^2 R$ loss (kw.)...............	24.0	37.8	60.0
Stray load loss (kw.)......................	18.0	25.5	42.3
For the open-circuit periods			
Rotor excitation (amperes)................	327	327	324
75-deg. rotor $I^2 R$ loss (kw.)...............	38.5	38.5	38.0
Terminal pressure (volts)................	8420	8420	8350
Core loss (kw.)..........................	270	270	260

Before these values were determined upon, curves of no-load excitation, short-circuit excitation, core loss and stray-load loss

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Alternators." On February 28, 1913 this and other "Methods of Testing Apparatus for Performance" were discussed at the Midwinter Convention of the A. I. E. E. For this discussion see pp. 714 to 721 of Vol. XXXII of TRANS. A. I. E. E.

had already been taken. These are reproduced in Figs. 4, 5, 6 and 7. The resistances of the windings had also been measured and reduced to the 75-deg. reference values.† The resistances were:

Stator winding per phase....................	0.0110 ohm
Rotor winding............................	0.360 ohm

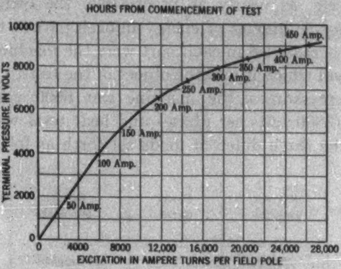

FIG. 4—NO-LOAD SATURATION CURVE OF 12-POLE—8750-KV-A.—6600 VOLT—500-REV. PER MIN.—THREE-PHASE GENERATOR

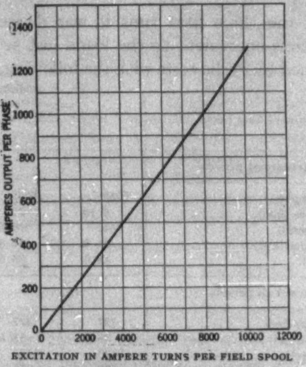

FIG. 5—SHORT-CIRCUIT EXCITATION CURVE OF 12-POLE—8750-KV-A.—6600-VOLT—500-REV. PER MIN.—THREE-PHASE GENERATOR

The value of the internal windage was estimated to be 30.0 kw.

The extent of the equivalence to the actual losses for the three loads is seen from the data in the following table:

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†Section 432 of the American rules is to the effect that "the efficiency, of all loads, of all apparatus, shall be corrected to a reference temperature at 75 degrees."

		Losses during the:		Average losses during cyclic test	Losses corresponding to actual load of 7000 kv-a. at at P.F. = 1.00
		Open-circuit half of the cycle	Short-circuit half of the cycle		
HEAT RUN I	Stator I^2R	0	24.0	12.0	12.5
	Rotor I^2R	38.5	5.1	21.8	17.8
	Core loss	270.0	0	135.0	119.0
	Stray-load loss	0	18.0	9.0	11.5
	Internal windage	30.0	30.0	30.0	30.0
	Total loss =			207.8 kw.	190.8 kw

		Losses during the:		Average losses during cyclic test	Losses corresponding to actual load of 8750 kv-a. at P.F. = 0.80
		Open-circuit half of the cycle	Short-circuit half of the cycle		
HEAT RUN II	Stator I^2R	0	37.8	18.9	19.4
	Rotor I^2R	38.5	7.9	23.2	27.9
	Core loss	270.0	0	135.0	119.5
	Stray-load loss	0	25.5	12.8	15.3
	Internal windage	30.0	30.0	30.0	30.0
	Total loss =			219.9 kw.	212.1 kw.

		Losses during the:		Average losses during cyclic test	Losses corresponding to actual load of 10937 kv-a. at P.F. = 0.80
		Open-circuit half of the cycle	Short-circuit half of the cycle		
HEAT RUN III	Stator I^2R	0	60.0	30.0	30.5
	Rotor I^2R	38.0	12.4	25.2	32.6
	Core loss	260.0	0	130.0	120.0
	Stray-load loss	0	42.3	21.2	21.5
	Internal windage	30.0	30.0	30.0	30.0
	Total loss =			236.4 kw.	234.6 kw.

The temperatures of the circulating air were determined at the inlet and outlet from the mean of the readings of several thermometers. The results and the "loss per degree air rise," are given as follows:

Designation of heat run	Total loss in machine	Air rise in machine	Loss per degree air rise
I	208 kw.	12.4 deg.	16.8 kw.
II	220 kw.	13.0 "	16.9 kw.
III	236 kw.	15.5 "	15.3 kw.
Average value for loss per degree air rise			16.3 kw.

It can fairly be assumed for this particular design that the heat corresponding to 90 per cent of the loss in the machine is carried off by the circulating air, the remaining 10 per cent being dissipated from the surfaces of the machine.

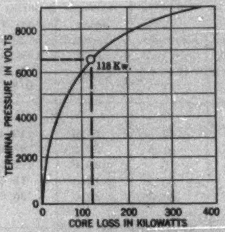

FIG. 6—CURVE OF CORE LOSS OF 12-POLE—8750-KV-A. — 6600-VOLT —500-REV. PER MIN. THREE-PHASE GENERATOR

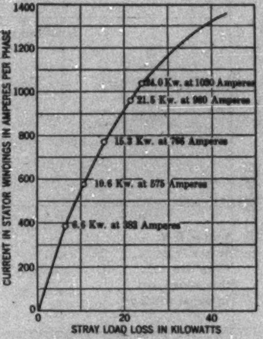

FIG. 7—CURVE OF STRAY LOAD-LOSS OF 12-POLE—8750-KV-A.—6600-VOLT—500-REV. PER MIN.—THREE-PHASE GENERATOR

Therefore we have, as carried away by the circulating air:

$$16.3 \times 0.90 = 14.7 \text{ kw. per degree rise.}$$

One kilowatt raises the temperature of 1000 cu. ft. of air per minute (0.47 cu. m. per second) by 1.78 deg., or:

A temperature rise of 1 deg. will be occasioned by a loss of 1 kilowatt for a circulation of 1780 cu. ft. per min.(0.84 cu. m. per second).

Consequently we have:

Quantity of circulating air = 14.7 × 1780 = 26,200 cu. ft. per min. (12.4 cu. m. per second).

In the following table are brought together for the three heat runs the results obtained by the embedded temperature detectors in the locations designated by A and B in Fig. 1, and also the results for the mean of A and B.

Designation of heat run		I	II	III
Total loss in machine		208 kw.	220 kw.	236 kw.
Temperature rises by embedded detectors	Location–A.	33.0 deg.	36.0 deg.	41.5 deg.
	Location–B.	26.3 "	28.8 "	29.3 "
	Mean of A & B.	29.7 "	32.4 "	35.4 "
Loss per degree of mean rise		7.00 kw.	6.80 kw.	6.70 kw.
Average for the three heat runs for the loss per deg. of mean rise		6.83 kilowatts		

It is to be noted that by mean rise by embedded detectors is meant the mean of the two maxima, the one being the maximum for location A and the other being the maximum for location B.

The results for these three heat runs by the cyclic method deviate from the average result by less than 3 per cent in the case of the "loss per degree mean rise by embedded detectors" and by only 6 per cent in the case of the "loss per degree air rise in machine." These values speak well for the accuracy of the cyclic test.

These and the temperature rises obtained at other parts are brought together in the following summary in which the results from which the highest "hottest spot" temperatures are deduced, are in heavy type.

Designation of heat run		I	II	III
Kilovolt amperes		7000	8750	10937
Power factor		1.00	0.80	0.80
Terminal pressure (volts)		6600	6600	6600
Current (amperes)		614	766	960
Maximum observed rise by temperature detectors		**33.0**	36.0	41.5
Observed by temperature detectors	In location "A"	33.0	36.0	41.5
	" " "B"	26.3	28.8	29.3
	Mean of A & B	29.7	32.4	35.4
Maximum observed rise of rotor wind-winding		19.0	19.0	20.5
Observed rise stator winding by resistance		**28.0**	**34.5**	**42.0**
Air rise in machine		12.4	13.0	15.5
Deduced hottest-spot temperature corresponding to ambient temp. of reference		78.0	84.5	92.0

It is interesting to note that in heat runs II and III the hottest-spot temperature corresponds to the observations of the rise of the stator winding by resistance and not to the results obtained by the embedded detectors. This is for the reason that the Standardization Rules require 10 deg. to be added to the observed temperature as determined by the resistance method and require 5 deg. to be added to the observed temperature as determined from the highest reading of any of the embedded

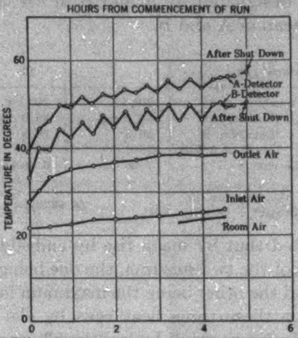

FIG. 8—TEMPERATURE-TIME CURVES FOR CYCLIC HEAT RUN EQUIVALENT TO 7000 KV-A. AT POWER FACTOR = 1.00

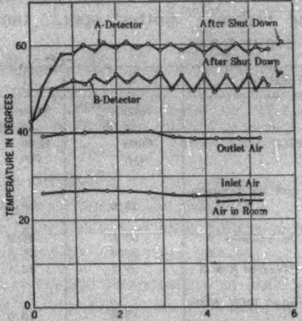

FIG. 9—TEMPERATURE-TIME CURVES FOR CYCLIC HEAT RUN EQUIVALENT TO 8750 KV-A. AT POWER FACTOR = 0.80

detectors. Such results may occur in machines so designed that no part of the stator winding is much hotter or cooler than the *average* temperature of the stator windings.

In Figs. 8, 9 and 10 are given curves showing the progress of the heating during the cyclic tests.

It should be understood that this paper has been chiefly confined to a discussion of those parts of the temperature sections of the rules which deal with rotating machinery and that even in this small portion of the rules there are various matters of interest and importance which have not been considered. On the subject of transformers there are further matters of importance in the temperature sections. The sections on dielectric tests and those on efficiency and regulation present features of at least equal importance as regards both rotating machinery and transformers.

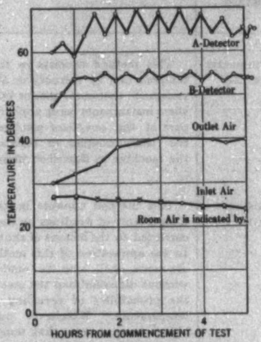

FIG. 10.—TEMPERATURE-TIME CURVES FOR CYCLIC HEAT RUN EQUIVALENT TO 10,937 KV-A. AT POWER FACTOR = 0.8

The author entertains the hope that his paper soon may constitute one of several papers by others along these general lines and that by making this beginning he may have promoted in some measure the important undertaking of standardization of electrical machinery.

APPENDIX

A COMPARISON OF THE TEMPERATURE LIMITS IN THE BRITISH AND THE AMERICAN RULES FOR ELECTRICAL MACHINERY

In the following collection of Tables the three methods of determining the temperature are designated I, II and III, following the arrangement in the American rules. Briefly these methods are defined in the American rules as follows:

Designating number of method	Designating name of method	Description of method
I	Thermometer method	This method consists in the determination of the temperature, by mercury or alcohol thermometers, by resistance thermometers, or by thermocouples, any of these instruments being applied to the hottest accessible part of the *completed* machine, as distinguished from the thermocouples or resistance coils *embedded in* the machine as described under Method No. III.
II	Resistance method	This method consists in the measurement of the temperature of windings by their increase in resistance, corrected to the instant of shut-down, when necessary. In the application of this method, thermometer measurements shall also be made whenever practicable without disassembling the machine, in order to increase the probability of revealing the highest observable temperature. Whichever measurement yields the higher temperature, that temperature shall be taken as the "highest observable" temperature.
III	Embedded-temperature-detector method	This method consists in the use of thermo-couples or resistance temperature detectors, located as nearly as possible at the estimated hottest spot. When Method No. III is used, it shall, when required, be checked by Method No. II; the hottest spot shall then be taken to be the highest value by either method, the required correction factors being applied in each case.

1.—LIMITS OF OBSERVABLE TEMPERATURE FOR CLASS A MATERIALS WHEN METHODS I AND II ARE EMPLOYED

For these cases the limits are set forth on the first insert herewith.

2.—LIMITS OF OBSERVABLE TEMPERATURE FOR CLASS B MATERIALS WHEN METHODS I AND II ARE EMPLOYED

The second insert sets forth the limits for these cases.

LIMITS OF OBSERVABLE TEMPERATURE FOR: "CLAS
CUIT
INDU

BROAD DESCRIPTION OF THE PART OF THE MACHINE	BRITISH DESIGNATING NUMBERS OF THE ITEMS (from p. 18 of the British Rules)	DETAIL DESCRIPTION OF THE PART OF THE MACHINE		
Stationary and rotating d-c field coils	1 and 2	Shunt or separately excited field coils		Me
		Series field coils and compensating and commutating coils.		
		Bare windings, such as an edgewise strip conductor or cast copper windings.		Ma visio
Rotating armatures with commutators	4 and 5	Rotating armatures with commutators		
A-c. windings in slots (of the ratings for which method III is not required)	7 and 8	Stator (induced winding) of synchronous motor or alternator	For 5000 volts and above	95 each ther pres (Me whe plica
			For less than 5000 volts	90 is whe ticab
		Stator and rotor of non-synchronous motor or alternator	For 5000 volts and above	95 each ther pres (Me whe plica
			For less than 5000 volts	90 is whe ticab
Short-circuited windings	10	Insulated		
	11	Uninsulated		
Air-cooled transformers	14 and 15			
Oil-immersed transformer	17	Windings		
	18	Oil		
Induction regulators				N indu tish
Iron cores	19	For British		

NOTE. Both the British and the American rules state that fo
temperature limits shall be 10 deg. C below the limits fixed for

MATERIAL; SHORT-CIR-
NDINGS; TRANSFORMERS;
REGULATORS; IRON CORES } WHEN METHODS I AND II ARE EMPLOYED

LIMITS OF OBSERVABLE TEMPERATURE

METHOD I		METHOD II		
H RULES	A. I. E. E. RULES	BRITISH RULES	A. I. E. E. RULES	
is not allowed	90 deg.	95 deg.	95 deg.	
deg.	90 deg.	Method II is not allowed	Method II is not allowed	
specific provi- ch windings	100 deg.	Makes no specific provision for such windings	95 deg.	
deg.	90 deg.	Method II is not allowed	95 deg.	
nus 1½ deg. for volts or part which the rated ceeds 5000 volts. s only allowed od II is inap-	90 deg.	95 deg. minus 1½ deg. for each 1000 volts or part thereof by which the rated pressure exceeds 5000 volts	95 deg.	
hen method II ble. 95 deg. d II is imprac-	90 deg.	95 deg.	95 deg.	
inus 1½ deg. for volts or part which the rated ceeds 5000 volts. is only allowed od II is inap-	90 deg.	95 deg. minus 1½ deg. for each 1000 volts or part thereof by which the rated pressure exceeds 5000 volts	95 deg.	
hen method II ble. 95 deg. d II is imprac-	90 deg.	95 deg.	95 deg.	
0 deg.	"The temperature rise may be of any value such as will not occasion mechanical injury to the machine" (see section 388)	Method II is not applicable to short-circuited windings		
deg.				
Method I is not allowed		95 deg.	95 deg.	
Method I is not allowed		95 deg.	Oil immersed without water cooling	95 deg.
			Oil immersed with water cooling	80 deg.
0 deg.	90 deg.	Method II is not applicable		
ic provision for gulators in Bri-	Method I is not allowed	No specific provision for induction regulators in British rules	Temperature rules for induction regulators same as for transformers	

their sections 42 and 43. For A. I. E. E. rules, see A. I. E. E. section 391

s, silk, paper and similar materials when neither impregnated nor immersed in oil, the
materials.

[HOBART]

LIMITS OF OBSERVABLE TEMPERATURE FOR: CO

BROAD DESCRIPTION OF THE PART OF THE MACHINE	BRITISH DESIGNATING NUMBERS OF THE ITEMS. (From p. 18 of the British Rules.)	DETAIL DESCRIPTION OF THE PART OF THE MACHINE		
Stationary and rotating d-c. field coils	3	Shunt or separately-excited field coils.		N
		Series field coils and compensating and commutating coils.		
		Bare windings, such as an edgewise strip conductor, or cast copper windings		N sion
Rotating armatures with commutators	6	Rotating armatures with commutators		
A-c. windings in slots (of the ratings for which method III is not required).	9	Stator (induced winding) of synchronous motor or alternator	For 5000 volts and above	1 for the pre (m low ina
			For less than 5000 volts	1 is wh tica
		Stator and rotor of non-synchronous motor or alternator	For 5000 volts and above	1 for the pre (m wh plic
			For less than 5000 volts	110 pra me
Commutators	12			
Slip-rings	13			
Air-cooled transformers	16			

ASS B" MATERIALS
AND FOR
ATORS AND SLIP RINGS } WHEN METHODS I AND II ARE EMPLOYED.

LIMITS OF OBSERVABLE TEMPERATURE

METHOD I		METHOD II	
SH RULES	A. I. E. E. RULES	BRITISH RULES	A. I. E. E. RULES
I is not allowed	110 deg.	115 deg.	115 deg.
15 deg.	110 deg.	Method II is not allowed	Method II is not allowed
o specific provi- h windings	120 deg.	Makes no specific provision for such windings	115 deg.
10 deg.	110 deg.	Method II is not allowed	115 deg.
minus 1½ deg. 00 volts or part which the rated ceeds 5000 volts I is only al- n method II is e)	110 deg.	115 deg. minus 1½ deg. for each 1000 volts or part thereof by which the rated pressure exceeds 5000 volts	115 deg.
when method II ble. 115 deg. od II is imprac-	110 deg.	115 deg.	115 deg.
. minus 1½ deg. 00 volts or part which the rated ceeds 5000 volts is only allowed hod II is inap-	110 deg.	115 deg. minus 1½ deg. for each 1000 volts or part thereof by which the rated pressure exceeds 5000 volts	115 deg.
hen method II is e. 115 deg. when is impracticable	110 deg.	115 deg.	115 deg.
90 deg.	See sections 390 and 347	Method II is not applicable to commutators	
90 deg.	See sections 389 and 347	Method II is not applicable to slip-rings	
Method I is not allowed		115 deg.	115 deg.

[HOBART]

3.—Limits of Observable Temperature for Class A and Class B Materials When Method III is Used

When Method III is used, the limits set forth in the British and American rules are identical and are set forth below for machines of various voltages.

Voltage of Machine	Permissible limits of temperature as measured by embedded temperature detectors			
	Temperature detectors located between top and bottom coil-sides in two-layer windings		Temperature detectors located between coil-side and core and between coil-side and wedge	
	Class A	Class B	Class A	Class B
Not over 5000 volts..........	100 degrees	120 degrees	95 degrees	115 degrees
Between 5000 & 6000 volts ..	100 "	120 "	94 "	114 "
" 6000 & 7000 "	100 "	120 "	93 "	113 "
" 7000 & 8000 "	100 "	120 "	92 "	112 "
" 8000 & 9000 "	100 "	120 "	91 "	111 "
" 9000 & 10000 "	100 "	120 "	90 "	110 "
" 10000 & 11000 "	100 "	120 "	89 "	109 "
" 11000 & 12000 "	100 "	120 "	88 "	108 "

Note: Method III, (Defined and discussed in sections 352 to 356 of the American Rules) is, in the American Rules, mandatory for all stators of machines (exclusive of induction regulators) with cores having a width of 50 cm. (20 inches) and over, and also for all machines of 5000 volts and over, if of over 500 kv-a., regardless of core width. The method is not mandatory in the British Rules but section 63 of those rules states that: "When so specified with the inquiry, embedded temperature detectors shall be employed in the case of a machine of over 3000 kilowatts if wound for a rated pressure exceeding 3300 volts."

Presented at the 325th meeting of the American Institute of Electrical Engineers, Philadelphia, Pa. October 13, 1916.

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THE POWER COMPANY'S PROBLEM IN THE ELECTRIC SUPPLY FOR LARGE SINGLE-PHASE LOAD

BY WILLIAM C. L. EGLIN

ABSTRACT OF PAPER

The position taken by the power company is that it should be able to supply all needs of energy in the community whether for industrial, street railway or trunk railroad use. The power company must also be able to supply energy of uniform pressure whether single-phase, two-phase or three-phase, at whatever voltage best suits the consumer. These conditions are best met by polyphase generating units, and three-phase units are almost universally adopted on account of the economy in transmission which they permit.

When the demand for single-phase current is heavy enough to produce an unbalance, some means of balancing must be provided in order to prevent reduction in the output of the generator, and also to maintain uniform voltage on all phases. Three methods of balancing are discussed; first, by equipping the generator field with damping devices; second, by the use of a separate machine similar to the three-phase induction motor; third, by means of a synchronous phase-balancer consisting of a two-unit machine, one of which transfers energy between phases and the other balances the voltage. Correction for power factor on each individual large consumer's line is suggested.

FUNDAMENTALLY, the power company should be prepared to supply electric energy for all the uses required in the territory which it serves. The greater the variety of utilization of the power company's service, the greater is the diversity factor—the non-coincident demands within a twenty-four hour period or within the yearly period of operation—which increases and improves both the daily and the yearly load factors, and enables the generating plant to operate more efficiently.

In order that it may furnish service in the simplest way, it is the policyand aim of the power company to select such voltages and frequencies for the generating equipment as are best adapted to meet the requirements of its consumers' apparatus. Practically without exception in this country at this time, the main generating stations of large power companies are equipped to supply polyphase alternating currents, at high voltages and at frequencies of either 25 cycles or 60 cycles.

A word in retrospect:

The power companies' principal business in their earlier period was lighting. The use of lighting is restricted usually to the hours of darkness, so that the period of maximum load was a relatively small percentage of each twenty-four hours. The diversity factor of this load, due to the combination of stores, residences and factories, did not improve the load factor very materially, on account of the occurrence simultaneously of these loads between the hours of four and six p.m., forming a very abrupt peak in the load diagrams, especially during the winter months. The value of a motor load was therefore recognized, because it would be more continuous and because its requirements for power would increase very considerably over the requirements for lighting.

The next logical step in increasing the load factor was the broad position taken by the power company, to supply all of the needs for energy in the community; first, by supplying energy to large industries; then, to the street railways; and finally, to the steam railways in its territory.

Another important and very obvious consideration, from the power company's standpoint, is to operate the plant at its maximum efficiency. This means loading the generating units with the load which will produce the maximum *steam economy* in a steam generating station and entail the minimum investment in plant.

The generating apparatus must be capable of delivering to the consumers, energy of uniform pressure, irrespective of the demands, and the power company must stand ready to supply single-phase, two-phase and three-phase current at any voltage that best suits the individual consumer. These conditions are best met by polyphase generating units; and on account of the economy in transmission, three-phase units are being universally adopted.

The power requirements of individual consumers in a large territory, are of a varied character, demanding a close regulation of pressure through a range of their loads from no-load to full load.

With the balanced three-phase load of a consumer there are no serious difficulties involved, and even with the two-phase load which can be partially balanced by means of T-connected transformers, the difficulties are of little importance, and can be taken care of either by individual automatic regulators on the feeders supplying the consumer, or by regulation of the generated voltage, or by both.

When the demand for single-phase load is heavy, and especially when it produces an unbalance—*i.e.* when a single consumer requires a large amount of single-phase load and it cannot be balanced by other consumers also requiring single-phase load, a number of new problems are presented: The capacity of the generating apparatus is materially reduced, on account of the load being limited by the carrying capacity of the windings in the heavily loaded phase, so that the first problem is to provide some means of balancing the single-phase load, or splitting the single-phase load on the generators, to enable the generator to be operated at its normal output. The second problem is to maintain uniform voltage on all phases irrespective of the unbalancing. There are several methods by which this may be partially accomplished:

First, by equipping the field of the generator with damping devices, which consist of copper conductors imbedded in the core and short-circuited at their ends; this enables the transfer of energy from the heavily-loaded phase to the under-loaded phase. It, however, cannot be an exact balancing of the load and does not permit of the balancing of potentials. When the unbalance exists only in one phase and is fixed, some adjustments can be made which will approximate uniform voltage upon all three phases. The addition of dampers to the generator, however, reduces its efficiency and adds to its size and necessarily to its first cost, and it would probably be necessary to equip all generators in this way. On the other hand, the balancer capacity is added only for the amount of unbalanced single-phase load.

Second, by the use of an external machine connected to the generator, similar in all respects to the three-phase induction motor. By the addition of boosters on each phase, regulation of voltage and also a balance may be effected. When the unbalance exists on one phase and it is known that this will always be the heavily-loaded phase, adjustments can be made in the windings of this rotating machine so as to obtain an average of balance of load and an average of balance of voltage.

Third, by means of a synchronous phase balancer, which consists of a two-unit machine, the function of one unit of which is principally to transfer energy between phases; the other unit is a boosting set with two fields at right angles to each other, which balances voltage. Thus, by use of the combination, there are maintained, uniform energy balance and uniform voltage balance. These fields may be controlled by automatic regulators, and a balanced voltage under wide variations from zero to the full range of the balancer set, may be obtained. Variations in load may occur on any phase, without in any way affecting its satisfactory operation. The operation of the balancer set does not, in any way, affect the economy of the generator. It does permit the generator to be operated at its most efficient load and to carry a full load, irrespective of the unbalance, up to the capacity of the balancer set.

The losses in the synchronous phase-balancer and booster are the usual losses in rotating synchronous apparatus, consisting of the losses in the windings and fields, windage and friction of its bearings. The efficiency of a machine of 5000 kw. is approximately 94 per cent.

As previously noted, two single-phase loads may be partially balanced by T-connected transformers, and naturally three or more single-phase loads may be distributed on the three phases so as to produce the best balancing effect; so that with the increased demands for single-phase load, additional balancer capacity may not be required in a large generating station.

Because of the fact that the balancer apparatus is a synchronous machine, the portion of the unit which is designed to transfer energy, will be made somewhat larger and could be used as a synchronous condenser to improve the power factor of the system.

The principal demand from large consumers is alternating current, either single-phase, two-phase or three-phase, at some predetermined, practically uniform voltage. With varying demands from no-load to full load, good regulation may be obtained by the various automatic devices to regulate the generating voltage on individual feeders. Variation in voltage upon feeders, however, may become excessive with inductive loads. These loads may also produce at the generating station a low power factor, with a consequent under-loading of the generators, reducing their capacity and possibly necessitating their operation at some point lower than their maximum steam economy.

There are great variations in the power factors of individual consumers, depending upon the nature of their loads. As this also prevents the economical loading of the generating units. some means should be provided to correct for power factor, and I believe that each individual large consumer should be corrected for practically unity power factor, and to do this the proper synchronous condenser capacity should be introduced at some point in the consumer's line where the most economical results can be obtained. This, however, will vary very largely with each individual consumer and must be studied in each case.

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SUPPLY OF SINGLE-PHASE LOADS FROM CENTRAL STATIONS

BY PHILIP TORCHIO

Abstract of Paper

American central stations, contrary to European practise, have extensively adopted single-phase distribution from polyphase stations, balancing the loads among the different phases by grouping of the single-phase feeders or the distributing substations. Voltage regulation for lighting circuits has been supplemented by individual regulators. Generators with good single-phase characteristics were sometimes employed. In other cases generators were installed of larger kilovolt-ampere rating than the kilowatt capacity of the steam unit.

Large customers, using electric welding machines, electric furnaces, etc., assist the balancing by dividing their load between the two or three phases.

In cases of railroad companies' generating stations, the single-phase power is furnished from three-phase generators of special design. In cases of purchased power from central stations, different methods of supply may be available.

In connection with the supply of service to the Western portion of the New Haven Railroad electrification by the New York lighting companies, four methods were considered contemplating the supply of power—(1) directly from the 25-cycle system busbars; (2) from a separate section of the 25-cycle system busbars; (3) from a 60-cycle station with frequency changers at the delivery point; (4) from special 25-cycle generators installed in the latter station. On account of the requirement of parallel operation with the railroad power plant, the first method would not give the necessary load control. The second method was dismissed on account of the requirements of balancers and also longer transmission lines than the other methods. The third plan necessitated a large investment in special apparatus and gave poor efficiency of conversion. The fourth method was adopted as it gave complete control of the load and voltage, and maximum efficiency of transmission. The larger original investment in new generator capacity was partly compensated for by its value to the companies as a standard equipment for supplying their future demands and other three-phase existing loads in the immediate districts. The equipment is described.

CONTRARY to European practise, the distribution of single-phase currents from polyphase stations is very common in American central station practise. The balancing of loads among different phases has been accomplished by grouping of single-phase feeders on different phases. The exacting requirements of regulation for lighting circuits have been met by supplementing the regulation obtained from the main supply with individual regulators on each single-phase feeder circuit. These circuits feed different districts.

Where the distribution is done from different substations, fed from a generating station, the transmitting lines between generating station and substations may be two- or three-phase, one of the phases carrying the heavy lighting load in addition to its share of the power load, which is equally divided among the phases. In such cases the substations are divided into two or three groups, each group having the heavily loaded phase connected to a different phase of the generating station, so that the loads of all phases are approximately equally divided.

The operation of such systems has never given any inconvenience. In the early years the distributing stations and the individual customers' loads were small, so that there were not presented great difficulties in balancing the load among different groups of feeders connected to different phases. With the growth of the system and the introduction of distributing substations, fed from a generating station, the unbalancing of phases became a problem, because it was not possible to maintain always balanced loads on different phases, notwithstanding the care taken in the grouping of different substations. In such cases generators were secured with suitable field windings and additional copper in the armature to give good single-phase characteristics; in other cases the generators were also built of greater kilovolt-ampere rating than the kilowatt capacity of the steam unit.

As an illustration of the former case, we may cite the 14,000-kw. three-phase, 10,000-kw., single-phase, 60-cycle generator installed in 1906 in the Waterside station of the New York Edison Company. As illustrations of the second case are the three 19,000-kv-a., 60-cycle generators driven by 15,000-kw. turbo units installed in 1913 in the 201st Street station of the United Electric Light & Power Company of New York. In this case the fields of the generators were also provided with damper windings which would permit them to carry 7500 kv-a., single-phase load. With this precaution taken, the station output is not handicapped by low power factor or unbalanced loads, and is capable of taking on a comparatively large single-phase customer without handicapping the generating capacity.

Usually the load unbalancings are only temporary and of relatively high power factor and, therefore, they do not present the same difficulties as when large single-phase loads, often of fluctuating character, are to be supplied. In such cases the customer can greatly assist the central station by dividing his load as nearly as possible between the two or three phases, as it will give a better balanced voltage condition. This is especially true in electric welding, electric furnaces and possibly in single-phase railroad supply. This division of load has been accomplished to good advantage in cases of large industrial installations.

When large amounts of single-phase railway load supply are to be furnished, the railroads have, from the beginning, established the practise of installing three-phase generators to furnish the bulk of the power single-phase, direct from the generators. The generators are of special design. In cases of purchased power from central stations, it may be possible to do away with the special design generators and supply the single-phase loads from the main buses of the power company, if of sufficient capacity, or with the aid of phase balancers or possibly by sectionalizing, on different phases, the railway load.

Vol. 35
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A very careful study of the most advantageous method of supplying a large single-phase railroad load was made in connection with the negotiations of the New York lighting companies for supplying the New York, New Haven & Hartford Railroad Company with the power for its western end. The conditions of service required the supply of a minimum guaranteed maximum (hourly) load of single-phase power of 6500 kw., at 70 per cent power factor, with momentary peaks of 250 per cent of this load. The supply was to be paralleled with the 35,510-kv-a., single-phase generating station of the New York, New Haven & Hartford Railroad Company at Cos Cob. Conditions for parallel operation were rendered favorable by the existence of two three-phase 11,000-volt lines over which a maximum synchronizing power of 10,500 kw. could be supplied to the lagging station, with approximately 23,500-kw. of power supplied from the leading station.

The supply was to be 25-cycle and capable of controlling its load to maintain a load factor as desired. In addition, the control was to be such as to divide the peak loads with the Cos Cob power station in proportion to the maximum one hour load taken from the respective sources.

The power was to be supplied at the West Farms Junction

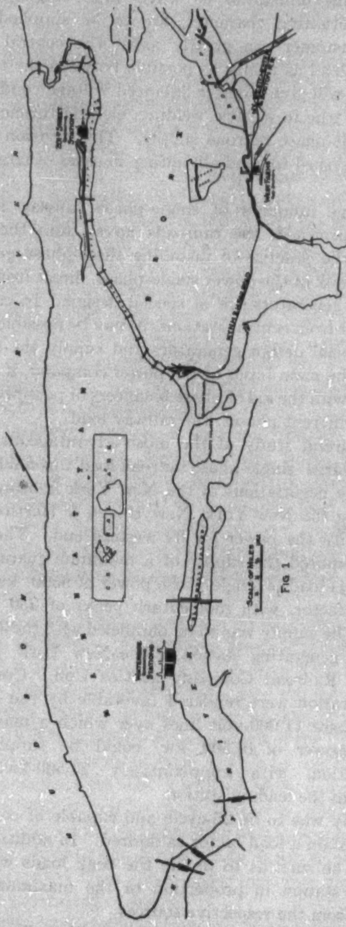
201st Street Station
Waterside Station
Waterside Stations
Scale of Miles

Fig 1

of the New York, New Haven & Hartford Railroad Company at 22,000 volts, single-phase, with the neutral grounded to the rails, and 11,000 volts, three-phase, for the synchronizing ties. The voltage was to be maintained at this supply point within the limits of 10,500 to 11,500 volts under all conditions of load. The generating capacity that was available for supplying this load at the time of these negotiations was 237,000 kw., 25 cycles, and 22,500 kw. 60 cycles, at the Waterside stations No. 1 and No. 2, located at 40th Street and East River, and 45,000 kw. 60 cycles at the 201st Street station, located at the Harlem River.

The accompanying map, Fig. 1, shows the relative locations of these stations to the proposed point of supply at West Farms. The distance over available duct routes from Waterside station is 9.5 miles, and from the 201st Station 4.5 miles.

With these stations available, the following methods of supply were considered:

I. Power supplied from the Waterside 25-cycle bus which has a generating capacity of 237,000 k.w. operating in parallel. Here the total capacity of the generators would be capable of absorbing the single-phase power without undue heating of the generators.

II. Power supplied from a section of the Waterside 25-cycle bus. In this case the generating capacity operating on this bus section would be comparatively small and phase balancers would be required to balance the load between the phases as the generators were not constructed for supplying a single-phase load greater than 10 to 15 per cent of the capacity of the machines.

In both propositions I and II, the voltage would be stepped up by means of transformers from 6600 to 24,000 volts in Waterside and transmitted at this voltage over 24,000-volt cables to the West Farms Junction of the New York, New Haven & Hartford Railroad.

III. Power supplied from the 201st Street 60-cycle station transmitted at the bus voltage of 7800 volts, three-phase to the West Farms Junction where it would be converted by means of frequency changers to 11,000 volts, 25 cycles.

IV. Special 25-cycle generators installed in the 201st Street station which would be capable of giving the required single-phase load in addition to supplying other 25-cycle load in this territory. Here the voltage would be stepped up to 24,000 volts and transmitted at this voltage to the West Farms Junction of the New York, New Haven & Hartford Railroad.

On studying these four propositions it was found that the first method would be impracticable as it would not give the necessary speed control for division of loads with the Cos Cob

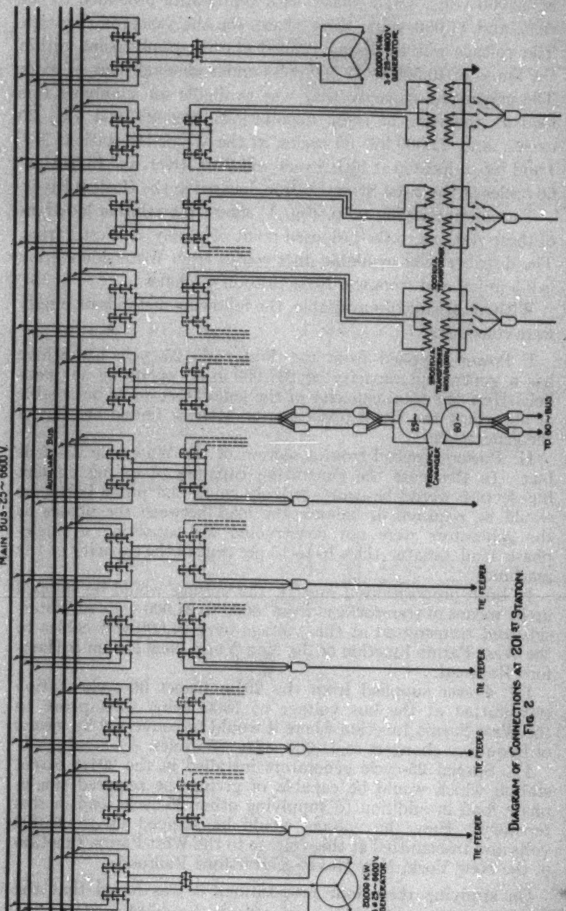
MAIN BUS-25~6600 V.
AUXILIARY BUS
20000 K.W. 3 φ 25~6600V GENERATOR
20000 K.W. 3 φ 25~6600V GENERATOR
FREQUENCY CHANGER
25~
60~
TO 60~BUS
TIE FEEDER
TIE FEEDER
TIE FEEDER
TIE FEEDER

DIAGRAM OF CONNECTIONS AT 201ST STATION.
FIG 2

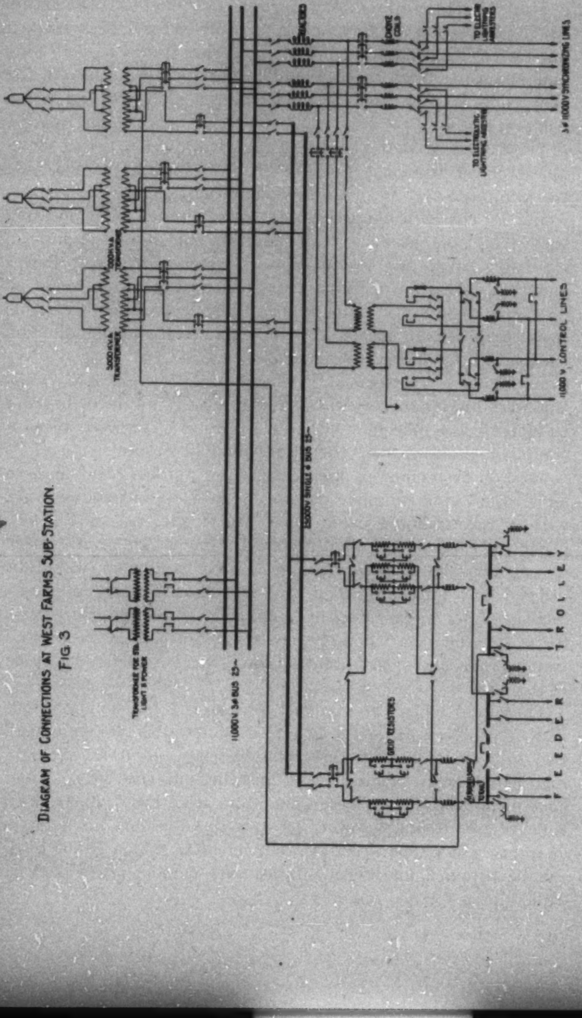
3000 K.V.A. TRANSFORMER
1000 K.V.A. TRANSFORMERS
REACTANCES
CHOKE COILS
TO ELECTROLYTIC LIGHTNING ARRESTERS
TO ELECTROLYTIC LIGHTNING ARRESTERS
3φ 11000V SYNCHRONIZING LINES
11000 V CONTROL LINES
25000V SINGLE φ BUS 25~
TRANSFORMER FOR STA. LIGHT & POWER
11000V 3φ BUS 25~
GRID RESISTORS
FEEDER
TROLLEY

DIAGRAM OF CONNECTIONS AT WEST FARMS SUB-STATION.
FIG 3

station. It would also not be possible to regulate the voltage supplied without the installation of an expensive regulator for this purpose.

Method II required the installation of phase balancers which was a new type of apparatus and had not been worked out by any manufacturer. The cable lines would be very long and expensive, and there would be no available space in the Waterside stations for installing the transformers and phase balancers.

The layout in method III had the advantages of taking three-phase power from the existing buses and therefore involving the minimum station investment, but the frequency converters would be costly and uneconomical, and limited in application exclusively to this service. In addition they would require an expensive substation for their installation at the West Farms Junction. Also, in order to give the load control, it would be necessary to have the motor of these frequency changers variable speed with certain specific drooping characteristics for dividing the load in the desired proportions with Cos Cob. Regenerative synchronous converter speed control in connection with rotor-wound induction motors was considered for this purpose in order to increase the efficiency of the conversion. This introduced a complicated and rather expensive system of supply.

Method IV seemed to offer the greatest number of advantages as it would give complete control of the load and voltage with a short transmission cable line. While the cost of the new generator capacity required involved a much larger outlay, still it was considered that ultimately such equipment would be utilized both for the railroad load as well as for the company's increasing demands. For this consideration the method proved to be the cheapest when the net results of capital outlay and transmission and transformation losses were considered as part of the cost.

Therefore, when the contract was signed for supplying the New York, New Haven & Hartford Railroad single-phase load, two 25-cycle, 6600-volt, three-phase turbo generators, having a high single-phase rating, were installed in the 201st Street generating station. These generators were rated 20,000 kw., three-phase, at unity power factor, with additional single-phase guarantees of 14,300 kv-a. continuous, after which 17,600 kv-a. can be supplied for seven minutes with a momentary peak of 21,000 kv-a. for two minutes.

The heavy single-phase rating of these generators was made possible by the use of special damper windings in the field poles. These windings were necessary in order to neutralize the pulsating armature reaction of single-phase load. The voltage of these generators was made 6600 volts, this being the company's system voltage.

In addition to the supply from these two generators, a frequency changer was connected between the 25- and 60-cycle buses in the 201st Street station. This 25-cycle bus can also transmit or receive power from the Waterside station through four 6000-kv-a. existing tie lines supplying power in the neighboring territory.

The power is stepped up in the 201st Street station to 24,000 volts by three 5500-kv-a., single-phase transformers, with 1000-kv-a. teaser transformers supplying the third leg. This gives a capacity of 11,000 kv-a., single-phase, with one bank and cable out of service, with sufficient three-phase capacity for holding the two generating stations in step during times of trouble on the single-phase lines. All transformers and cables are capable of giving 50 per cent overload for one hour following the full-load run, with a final 100 per cent overload for seven minutes and 150 per cent for one minute.

Figs. 2 and 3 show diagrammatically the method of connections in the 201st Street generating station and the West Farms substation where the connections are made to the New York, New Haven & Hartford Railroad lines.

This supply has now been in operation for fourteen months and has been continuous from the start without any interference or difficulty.

The above description of this supply is made very general as the details have already been published in the technical press.*

**Electrical World*, Vol. 66, No. 24, 1915, Page 1300 and Vol. 66, No. 25, 1915, Page 1365.

Electric Railway Journal, Vol. 46, No. 25, 1915, Page 1200.

DISCUSSION ON "THE POWER COMPANY'S PROBLEM IN THE ELECTRIC SUPPLY FOR LARGE SINGLE-PHASE LOAD" (EGLIN), "SUPPLY OF SINGLE-PHASE LOADS FROM CENTRAL STATIONS" (TORCHIO), PHILADELPHIA, PA., OCT. 13, 1916.

W. S. Murray: In the days of the not distant past, there can be found commentary very unfavorable to the system of single-phase traction, based upon whether that power, supplied from central stations of polyphase design, brought about unbalanced bus-bar voltages.

My negotiations for the 40,000,000 kw-hr. of single-phase current now supplied by the New York Edison Company to the New Haven road, were effected through Mr. Torchio, and the electrical construction details necessary to such a supply were perfected under joint co-operation of the engineering departments of the two companies. There have been no disappointing features in practical operation to mar the excellent operating results which we anticipated, and as outlined in the contract guarantee of power supply.

The safe and sane construction and regulation features of the power supply, bearing in mind the necessity of perfect continuity of service, in combination with synchronous operation with our own power station, have made this western supply to our electrification zone a most valuable adjunct.

Ten years ago the New Haven engineers elected the single-phase system of propulsion as properly applicable to the New Haven conditions and at that time it, of course, was necessary to decide on the phase characteristics of the generators to be installed in the power station, its location at Cos Cob, Conn., having been determined as the economic point for power distribution. In these earlier days the copper clad dampened field was not in vogue and as pointed out before, central stations would have looked askance at the proposition to furnish from their bus bars, a single-phase load in the amount necessary to the New Haven's requirements, on account of its unbalancing terminal voltage effect. The New Haven, therefore, had to solve this problem incident to its own power generation, and I think I can say that the cost to us of its solution was, for our own and for posterity's sake, a valuable investment. At this point it is of interest to say that what was immediately apparent to the engineers of the New Haven Road was the fact that the best economies of power house generation demanded balanced loads in the phases of the generators, while the exact reverse and controlling condition prevailed outside of the power house, in that the most economical distribution of line load could be effected by maintaining one phase over the entire system; thus the power house had to bow to the line.

The interesting step, however, that followed was not the selection of single-phase generators, but three-phase generators. I will not repeat here, what may be found in the archives of other papers in the Institute, regarding our early troubles incident to the unbalanced effect of single-phase generation by polyphase machines; these have been conquered by the copper clad field, and notwithstanding our three-phase machines are loaded to the extent of 80 per cent single-phase current, they are at the same time distributing three-phase current with terminal voltages, the maximum unbalancing of which is not greater than 15 per cent under average conditions. Anticipating that you may be interested in what the actual unbalances are, there follows readings which I had taken this week at Cos Cob station.

Cos Cob Peak Loads

Time	Phase Voltages			Load kw.
	1-2	2-3	1-3	
5:33 P. M.	12200	11600	13400	16000
5:36 "	12100	11600	13400	16500
5:38 "	12100	11700	13700	17000
5:42 "	12100	11600	13600	18000
5:48 "	12100	11500	13700	18000
5:54 "	12200	11600	13800	19000
6:08 "	12100	11500	13800	21500
6:16 "	12200	11500	13800	20000
6:22 "	12200	11500	13800	20000
6:30 "	12200	11500	13900	24000
Cos Cob Low Loads.				
1:42 A. M.	11700	11800	13500	5500
2:02 "	11900	11500	13300	4500
2:08 "	11900	11600	13000	2700
2:13 "	11900	11700	13100	3800
3:21 "	12300	11500	13000	2900
3:25 "	12300	11600	13000	3300
3:38 "	12300	11700	13000	2900
3:46 "	12300	11700	13000	3300
3:49 "	12200	11600	12900	3400
3:57 "	12300	11600	13100	3000

As Mr. Torchio has pointed out, the matter of unbalanced effects due to the supply of single-phase loads is no longer of real moment. There are many situations where the unbalancing effect (as in the case of the New Haven supply), without any other correction than that resulting from the operation of copper clad fields, is entirely satisfactory. For example, the three-phase current as supplied from our generators previously described, is used in lighting our stations and for the operation of synchronous motors and converters, operating in the substations of railway and lighting companies adjacent to our property.

If further refinement, however, in regard to unbalanced voltages is required, static or rotary balancers may be used. In every instance, however, the conditions of power supply should be especially studied. While making a special installation for the New Haven conditions, it is pointed out that this same equipment is practically standard and applicable to placing power on the buses of the station for general distribution, as demand may require. Other stations might demand a more perfect balance of terminal voltage on the three phases to be continually maintained on the busses of the power station, while supplying single phase from two of the phases. This can be accomplished through the medium of a balancer as brought out in Mr. Eglin's paper.

Peter Junkersfeld: I would like to call particular attention to the first paragraph in Mr. Eglin's paper, and particularly the first sentence.

He says, "fundamentally the power company should be prepared to supply electric power for all the uses required in the territory which it serves."

The remainder of his paper, and also Mr. Torchio's paper, shows one notable instance in which that has been done, and also points out the four different methods that were considered and the reasons that govern the final adoption of the one that was selected.

The general public who ride on the steam cars, who ride on the surface, elevated and subway cars, and who use electric service for light and power, are, after all, in the last analysis very largely one and the same; so that, if anything is done in an uneconomical manner, in any one of those branches, it to a certain extent involves the same people.

Certain of these uses for electric service come at one hour of the day and month, and certain other uses at another time of day and month; so that, if the fundamental statement that is made here is followed out, and followed out to the full, it results in the best economy for all concerned. That applies not only to the particular engineer who buys and installs the equipment, but also to the engineer who designs and manufactures the equipment.

These papers refer principally to the supplying of railway power in large centers from very large stations.

I think we all feel that ultimately the use of electric power will be very extensive, and that power will have to be supplied through widley scattered areas; and also that full consideration must be given to the dollars already invested, and these dollars used as far as practicable:

That, then immediately brings up certain further questions in the design of apparatus and the design and construction of lines. It will probably resolve itself into practically state-wide transmission.

In state-wide transmission it will be possible to connect up large sources of power, and take advantage of another fundamental factor, which, for the moment, we might call "capacity diversity," particularly in a large territory where there is a certain source of steam power or water power available.

There are a great many areas in this country where the water-power supply in the summer is very low, possibly within 50 or 100 miles (80.4 km. or 160.8 km.) of some place where there is a certain source of steam power supply, which has an excess of supply in the summer and a shortage in winter. Those two sources should help each other. The state-wide transmission lines, it might be conceived, could be used for the purpose of interchanging power between sources as well as delivering power to the steam railroads along their route.

That will mean that the balancing machines would probably have to be put at the points where the steam railroad supply is taken off and taken away from the state-wide transmission line.

D. B. Rushmore: The necessity for single-phase railway loads is an open question. There are, however, other single-phase loads which, under present conditions, are inevitable, and amongst the most important of these is the electric furnace. It would be interesting to hear from Mr. Eglin and from Mr. Torchio, what on their respective systems they would consider the maximum capacity of single-phase arc furnaces which would be permissible, these having a power factor of between 75 and 85 per cent.

The two systems outlined in the papers are different in respect to the overlapping of loads. Where single-phase generators are used the overlapping of loads comes only on the boiler equipment. On the other system, the single-phase electric load is transformed into a three-phase load on the electric circuits, and the possibility of obtaining desirable overlapping is very much greater.

It will also be interesting to know what is the minimum load for which single-phase generators would seem desirable.

L. E. Imlay: We have no single-phase problem at Niagara Falls. We have no single-phase railways.

It is true that we operate a number of furnaces on single phase, perhaps 2000-kw. capacity is the largest, but our substations and our switch stations are so arranged that these furnaces can be changed from one phase to another.

Our customers are so glad to get power that they are willing to take it not only when we want them to, but they are glad to put it on any phase that we ask them to put it on, so that, we have had no trouble whatever from unbalanced loads.

H. R. Summerhayes: While 2000 kw., as mentioned by Mr. Imlay may not be a large single-phase load to put on the Niagara system, it would be a very large load, and rather disconcerting in its effect on a small system; and it is quite possible that a balancer of the type used in Philadelphia could be applied with good effect where a single-phase load of 2000 kw. was to be taken from a comparatively small system.

When we get to as small a load as 2000 kw., however, the question of the comparative cost of the balancer and of the single-phase motor generator becomes interesting, and I should say that at that point there would be considerable question whether the balancer would generally be cheaper than the motor.

The balancer, however, would probably be more efficient, even in that size.

In larger sizes I believe that Mr. Doherty intends to present some figures indicating that the balancer is both cheaper and more efficient, hence its adoption by the Philadelphia Electric Company for this single-phase railway problem.

The balancer will have an application also in this way: that furnace loads need no longer be limited to 2000 kw.

Larger single-phase furnaces may be used if machines of the character of this balancer are used with them.

In Mr. Torchio's paper, this explains very clearly the reasons why single-phase generation was adopted, and there are undoubtedly advantages in having these single-phase systems entirely separate from the general three-phase supply of the New York Edison Company.

It is possible, however, that by the addition of a balancer, the two systems could be tied together, gaining somewhat in load factor. That is, the diversity factor would be improved.

N. W. Storer: It is very gratifying to note that the problem of applying single-phase power which has been presented to the central station companies has been met so satisfactorily.

We have two instances here, one in New York and one in Philadelphia, where the same problem has been met in two different ways, and both of them are giving entire satisfaction to the power users, and to the central station companies.

The question that is going to be the most interesting to the future users of power is, what is it going to cost to produce single-phase power in large blocks?

Is it going to cost more than three-phase power, and if so, how much, and at what load does this different cost begin?

E. H. Martindale: I would like to ask what power factor is obtained on single-phase railway load, with and without the balancing set, and also whether the use of damping coils has any effect on the power factor?

E. F. W. Alexanderson: If I understand the question correctly, it is whether the use of a balancer improves the power factor of the single-phase load, so as to make it more adaptable to the three-phase power system.

If desired, the balancer can be made to act as a synchronous condenser.

That question was considered in designing the balancer for Philadelphia, and it was concluded that it was better to design these machines exclusively as balancers; in other words, having the function only of converting power from single phase into polyphase, but not to correct power factor.

The power factor correction is being accomplished on the single-phase line with condensers when the load is high enough to require it.

John L. Harper: In the days when property existed in water rights, and water power was available at Niagara Falls, New

York, for the benefit of industrial interests of the country, we used to sell power for $20.00 per horse power per year.

Within the last few months we had calls for amounts of power ranging from 5000 to 25,000 horse power, which we could not furnish. Power asked for in some previous calls has now been obtained in other places, because we could not furnish it in a single-phase form.

The motor-generator set would impose relatively high losses upon a customer in making the change, and certainly much greater loss than would have been obtained if the power were changed by this new system of phase rearrangement. I understood the previous speaker to say that 94 per cent efficiency could be obtained, or a maximum loss of 6 per cent would be the greatest that could occur in an apparatus of this new form and, if such is the case, it would mean that a customer purchasing power from us would now only be under a handicap of $1.20 per horse power for getting his energy changed from three-phase to single-phase. At least in one case within my knowledge, a customer has gone elsewhere for power, where, it is reported, he could get it for $21.60 per horse power.

If this new apparatus really shows the efficiency that has been stated here, this customer could have stayed at Niagara Falls and received the benefit of a lower price than he could get if he moved elsewhere, and would not have had to duplicate his plant.

The large amounts of electric furnace power that are now being demanded, especially in the production of artificial abrasives, make this problem not only of interest from an engineering, but also from a financial standpoint.

H. W. Buck: I would like to ask whether it was not possible for the prospective customer to balance his load between the three phases. Why was it necessary to put the whole load on a single phase?

John L. Harper: The power which was demanded from us could not be used in three separate loads; the customer wanted only power enough to begin with to take up one or two of the three phases. To make the balance delivery from our lines, in this case where the customer's furnaces were approximately 2000 kw., it would have required the customer to have always increased his use of power in blocks of 6000 kw., which is much greater than the ordinary industrial development wishes to take at one time, preferring rather to enlarge in smaller increments.

H. W. Buck: It seems to me, in this connection, that with the rapid development of the electric furnace and furnace loads on central stations, power companies should take a very strong stand in insisting upon the balancing of such furnace loads between the various phases of the power system, and should try and force the electrochemical customer, as far as possible, to adopt this method of operation.

If the power companies simply swallow any single-phase proposition, however large, which may be thrown on one phase of their system by a customer, and then undertake to overcome it by installing a complication of balancers, trouble will result from the additional expense and additional complications. These balancers should be avoided wherever possible.

J. E. Kershner: I would like to ask for a little information on the manner of balancing fields controlled by automatic regulators.

I did not see how you could take fields of different phases and balance them—just what does that mean? You could not very well do that on an ordinary generator.

C. F. Scott: Something has been said of rather taking it for granted that the balancer is needed.

Looking at the question broadly, is the balancer needed?

Is it a universal panacea, or does it apply to certain specific cases?

The problems that have been presented are those of the larger sort. Most of the gentlemen who have spoken have been connected with three of the largest central stations in the country or with Niagara Falls, or the largest single-phase railways.

What may apply there, and some of the recommendations that Mr. Eglin has made, I think will be found to apply to the larger consideration of power and its distribution.

Broadly speaking, and to take a different position from the position which has been presented, is it not better to do away with balancers and auxiliaries and to meet the single-phase requirement in the generator itself?

As an illustration of what I mean, the synchronous condenser for power-factor correction has been looked upon as a great thing for increasing the capacity of a generator.

If for example a certain load is 1000 kv-a. at 60 per cent power factor, we have two alternatives, (a) a 1000-kv-a. generator to operate at 60 per cent. power factor or, (b) a 600-kw. generator supplemented by a 800-kv-a. synchronous condenser. In the latter case the aggregate capacity is 1400 kv-a. If there be a transmission line, its cost will be less if the synchronous condenser is placed at the load end, thus compensating for the extra cost of machinery.

If we can, by increasing the size of the generating unit, secure the capacity for supplying single-phase power, will not that be simpler than the addition of auxiliary apparatus?

We will be adding to the size of an already large unit where the cost for the additional kilowatt capacity is relatively small.

The power lost in a single power generator will generally be less than is required when there is auxiliary smaller apparatus. The attendance is less.

These remarks may not apply to the specially large cases which have been mentioned, but they certainly, I believe, will be applicable to smaller stations and smaller power units.

Again, two distinct cases arise, reconstruction and new construction. If a generator is now installed its capacity may be increased in the simplest way by the addition of a synchronous condenser or by a phase balancer; but if the construction is not new, it might be simpler to simply add to the size of the initial machine.

Take the cases brought out at Niagara Falls; The present generators are inadequate for a certain single-phase load. Those generators might be aided by auxiliary apparatus, but for new construction, would it not be simpler to add fifty per cent or whatever might be necessary to the size of those generators for the single-phase capacity required.

Fluctuation of the single-phase load is a factor which has not been brought out. The loads to which Mr. Imlay referred, which ran along so quietly, may relate to a certain type of furnace, which takes a substantially constant output for 24 hours.

Mr. Murray does not supply that kind of load. His is the other kind, up and down, in which the kind of regulation and method of providing the generating apparatus might be quite different.

Mr. Eglin suggests that each customer might be required to provide a power-factor regulator, so that there would be 100 per cent power factor to each individual customer.

There again, you must be implying customers who require a very large amount of power on a very large scale; and even then it seems to me it would be open to question, without an examination of the particular circuits, whether it would not be better in the central station to provide for supplying certain loads at the lower power factor than it would be to add synchronous apparatus over the system on each customer's premises for the adjustment of power factor.

Unless units are quite large it would certainly be better to have that general control in the hands of the central station than to have the regulation of the system somewhat under the control of each individual customer.

W. C. L. Eglin: Mr. Summerhayes says that there is a possibility of the motor-generator set being substituted for the balancer set. We do not believe that, from a central power company standpoint.

Mr. Junkersfeld stated that the power company must be ready to supply customers with any kind of requirement, whether they are big, or whether they are little. If we could have all of the load at unity power factor the balancing feature would be very small; that is, our troubles would be about cut in two, or probably more.

A central station power company has two things to consider; first, that it has got to buy its apparatus at the lowest price; second, it has got to get the most economical apparatus.

Now, Mr. Torchio just hinted at the possibility of designing generators for something less than unity power factor. If you do that, somebody will want a factor of 50, 60 or 70. You will have no uniformity, and no standard at all. You have got to begin somewhere, and the right place to begin it seems to me is at 100 per cent power factor, so that you can specify your machines to be operated at 100 per cent power factor, and you have got your system economized for load all the way up and down. Then, if you can load your machines at their proper load, you can generate at the maximum economy.

Next is the problem which affects the distribution of the energy to the consumer. Here again trouble comes in from the power companies' point of view. What is the character of that power?

If there are very rapid fluctuations in load, it requires certain methods of handling, or if it is a bulk power, such as five or six thousand kilowatts, it may be divided and you have no unbalanced condition to treat at all.

On the other hand, if you are installing balancer capacity, you put in balancer capacity only for the average unbalance of your system. As your single-phase loads grow the balancer capacity is not increased, that stays the same; so that you do not have to add either expensive alterations to your generators by making them larger, and adding dampers to them. You have your generators as efficient as they can be made. You only correct for the average condition. The more consumers you get the better off you are.

I would not worry the least bit about any furnace that I have heard mentioned today, because we are taking care of 20,000-kw. single-phase swings without any trouble at all, so that even with a very small power factor I would certainly not advise—I would not recommend the introduction of a motor-generator set, because the next customer who comes along has got to have another generator set; you cannot balance them very well, and you are adding to your investment cost. As I said before, what we are really aiming at is to keep our investment cost as low as possible.

Another question was asked with reference to the balancing of the fields.

I said the function of the booster was to balance the voltage.

There are two functions of the machine. One is to balance power, and the other is to balance voltage; and the purpose of the two fields is to compensate all of the three phases for any unbalanced condition of any of them.

Philip Torchio: I think the only direct question was raised by Mr. Summerhayes regarding the reason why we did not supply the railway load from our system bus.

We did not do it because we had to divide, in due proportion, the loads between our plant and the other station of the railroad company. If we had run our 200,000-kw. bus in parallel with the railroad, we would have taken all the heavy swings and introduced complications in the operation of the customer's station, which, after investigation of existing experience, we considered undesirable.

Mr. Summerhayes also asked the question of how a small company, having 1000 or 1500-kw. load, should take care of a prospective customer having a 2000-kw. single-phase load.

Such a company with a small installation of 2000 or 3000 kw. cannot handle 2000-kw. additional load without additional generating units; and here is the place to install generators with single-phase characteristics. The balancer or the motor-generator set is all right, if we can do the service with the existing equipment, but if we must install new generating apparatus, don't let us put ourselves in the same position that we are in now, that when a new customer comes along that wants 1000 or 2000-kw. single-phase we must again go to the manufacturers and put their engineers to their wits' ends to find out what they can do to rectify this load for us. Put capacity enough in the generators to take care of a liberal unbalanced load regardless of whether you will also use a balancer or not.

I do not think either, that Mr. Eglin is right when he says that generators should be designed for 100-per cent power factor. A commercial load generator should be designed for power factors lower than unity, at least eighty or eighty-five. We put, in 201st Street, the largest generator we could put on a 15,000-kw. turbine. The manufacturers said originally that they could make it 16, then refigured and went up to 19. We wanted 20, but 19 was the limit that the tensile strength of the material would allow, and we got a 19,000-kw. generator for a 15,000-kw. turbine, which runs at the most economical efficiency at 13,000 or 14,000 kw.; we lose some in slightly lower efficiency in having a larger generator, but we have the use of the full capacity of the unit at all practical conditions of power factor and unbalanced loads, which is more important.

In answering Mr. Rushmore's question—"What is the largest single-phase load we carry?"—The United Company's load is mainly single phase. I think the largest load of one district is at least 7000 or 8000 kw. We have three such single-phase loads, and we have operated them for years, at least ten years. Why should we have special apparatus in our stations to take care of some unbalanced loads, which will add to the cost of the equipment and station operation?

Regarding the handling of single-phase customers, this was pointed out by Mr. Buck. If a customer comes along and says he wants a furnace load of 6000 kw. and we know that he has three or four or five furnaces, we tell him that we will not furnish the service unless he distributes those three or four or five loads on different phases. That is done in different plants with large welding loads and furnace work—there is no difficulty about it; it is a logical, sensible way of solving the problem.

N. W. Storer: I have waited in vain for a reply to the question which I asked as to what this single-phase power costs?

If a power company can produce it—and it has been proven conclusively that they can supply the single-phase load—how much more is it going to cost?

Why should not they furnish single-phase power if the customer is to pay for it?

Farley Osgood: I would like to ask Mr. Eglin to tell us why he prefers purchasing machines at 100-per cent power factor, as against what you can conceive to be the probable average power factor per cent of his system as a whole, which is the practise at present with some companies?

C. F. Harding (communicated after adjournment): For many years we have been familiar with the advantages of a large diversity of load and a high load factor upon a power station furnishing either railway or lighting and power service. The very effective results obtained during the last few years by the Commonwealth Edison Company in Chicago by the consolidation of these three types of loads upon a single generating system, have made us realize that this same principle of great diversity of load and high load factor may well be extended beyond the individual loads to entire railway and lighting systems.

As an example I wish to emphasize the figures recently presented by an official of this corporation which indicate that the addition of a double peaked railway load, with an hourly maximum demand of 204,000 kw., to a light and power load with a single peak of 156,000 kw., raised the daily load factor from 52.5 per cent to 59.3 per cent. This also resulted in a saving in reserve capacity of 21,000 kw. of equipment over that which would have been required with the loads furnished from separate systems. If the estimated load which will be required by the electrification of the steam railroads entering Chicago be added as well, the load factor for a typical October day would reach 62 per cent.

Is it not possible and desirable therefore, to carry this line of reasoning a step further and secure as much single-phase load and as great a diversity of such loads as possible, provided the consumers demand cannot be met with a polyphase service? With the increase in single-phase traction, furnace loads and other single-phase power demands, not only will the difficulties in balancing a three-phase system with a variety of single-phase loads be lessened, but the load factor of the system will be simultaneously increased as well. It should be kept in mind that practically all single-phase loads which may be secured for a single system are of long hour duration and that the addition of any such loads which make more of the reserve equipment available for greater periods of time, simply results in eliminating fixed charges upon superfluous equipment which would otherwise have to be borne by the consumer.

Such a saving with separate single-phase generators in the station would affect the steam equipment only. With the use of some system which permits single-phase load to be furnished satisfactorily from polyphase generators, the saving in fixed charges is made applicable to the electrical apparatus in the power station as well. Ultimately, if the single-phase load is sufficiently large and diversified, it may be balanced upon the three-phase busses of the substation, in which case the substation equipment and the transmission lines profit by the higher load factor. Thus it seems that the policy of balancing as many varied single-phase loads or portions of such loads as possible upon a single polyphase system, is of importance from the standpoint of saving in fixed charges as well, and that with many large systems the converter and balancer will be considered as more or less temporary expedients to balance the loads during the period of acquisition of a sufficient amount and variety of single-phase loads to permit a permanent balance of the phases by proper distribution of such loads upon the various busses of a three-phase system.

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SINGLE-PHASE POWER PRODUCTION

BY E. F. W. ALEXANDERSON AND G. H. HILL

Abstract of Paper

The general tendency of the electric power supply industry is toward the centralization of power stations, embracing a variety of loads. In order to be consistent with this development it is highly desirable that power stations be standardized in essential features, so that they may combine their resources toward the ideal arrangement. The production of single-phase power should not interfere with this general scheme. Looked at from this standpoint, single-phase power can best be produced from polyphase systems. Means are suggested for producing single-phase power without interfering with the broad usefulness of the power station. The mode of operation and theory of phase converters is discussed with particular reference to its adaptability for permitting single-phase power to be derived from polyphase circuits.

IN VIEW of the universal use by power companies of polyphase generation and transmission of electric power for general purposes, the production and delivery of single-phase power must be considered as a special problem.

No power company would or could afford to install a single-phase plant unless its sole purpose was to furnish power to a load that requires single-phase power. In other words, it is settled that polyphase generation and transmission is most efficient, flexible and economical, and the problem presented to power companies when the demand for single-phase power appears is how this may best be produced or derived from their polyphase systems.

Indeed it may be well to extend the problem to cover those cases where such large amounts of single-phase power are required as to apparently justify a special power house and to inquire whether it might not be preferable in such a case to generate and transmit by polyphase and derive the single-phase when and where needed.

Probably the strongest argument for such a view is the practical wisdom in standardizing the electric systems of the country so that they may be tied together as occasion and opportunity permit with a minimum of elaborate and power-consuming transforming apparatus. This idea of consolidation and cooperation has recently been given serious attention by many of our ablest men who appreciate the great value of diversified loads and the greater economic efficiency to be obtained by covering the greatest field possible from a common source of electric power supply. It is prudent therefore to condition any conclusion that involves power production with the essential requirement that it be consistent with this general tendency.

The rapid growth of electric power systems makes this a most practical consideration. There are enough differences between electric transmission systems as they now exist without introducing still further complications.

Differences in voltages can not be avoided but to equalize this does not entail great loss of efficiency or undesirable features.

Differences in frequency are more serious and the process of decision upon the most desirable frequency for general use has resulted in adopting a variety of frequencies in different localities. As we now look upon 60 cycles as standard, the use of 50, 40, 30, 25 and possibly other frequencies can not but be regarded as unfortunate since practical considerations will sooner or later force the systems having odd frequencies to seek means to free themselves from the handicap they entail. There are many excellent systems and stations using 25-cycle power and the reasons for adopting 25 cycles were good and sufficient when they were established. Without, therefore, criticising the engineering of these plants, it may be stated that they could be duplicated today with 60-cycle apparatus for less than the original cost and with a distinct gain in general economic usefulness and value.

It seems a logical and highly practical conclusion that general policy should be opposed to the establishment to any considerable extent of power systems having peculiar or special features making them inadaptable to efficient connection with other systems in the vicinity.

Single-phase power may be obtained by:

1. Separate generating and distribution systems designed for single-phase load.

2. Polyphase generation and distribution of single phase load between the phases so that in effect the load becomes a polyphase load.

3. Generation and transmission as polyphase with motor-generator sets at substations.

4. Mixed single-phase and polyphase load furnished by the same distribution system in combination with methods for correcting the unbalancing effect of the single-phase load.

The first method comes under the head of special and abnormal development already discussed. It has, besides the disadvantages mentioned, the further disadvantage, as regards the generator, of increased size, weight and cost and lower efficiency as compared with polyphase generators. Single- phase generators have been built only for 25 cycles or lower and to a limited extent for special purposes. As compared with other ways of obtaining single-phase power this method seems to offer the least promise of general usefulness.

The second method has the advantage of the polyphase alternator. It is generally used for incandescent lighting distribution and for power and heating where the unit of energy capacity is small and adapted to division between the phases so as to result in very little, if any, unbalancing. It has been proposed and used to a limited extent for heavy single-phase loads, but the difficulty of preserving even an approximate balance between phases makes this method insufficient for large power requirements. It has the further disadvantage of requiring generators of the same frequency as the load demands.

Method No. 3 has the advantage of entire freedom as to generator and transmission and permits a single-phase load of any frequency or power factor to be drawn from any standard polyphase system without disturbing the balance or regulation. It provides means, moreover, of improving the power factor of the system by synchronous motors and from the power system standpoint is the most desirable of all methods when large unit amounts of single-phase power are demanded. It is the only method of producing low-frequency single-phase power from a 60-cycle system. The only objection that is made to this method is the cost of motor-generator sets and the cost of attendance.

The first cost of equipment, it is true, is greater than static transformers alone, but this is balanced to some degree by lower costs at the power station and in the transmission line, and is fully justified in a large power system since it makes it possible to combine the single-phase load with the general load and obtain the benefit of a higher load factor.

The cost of attendance is frequently made negligible by so locating the substations that the attendants may have other duties. The expense of attendance in any case is a small percentage of operating costs and can be entirely eliminated by introducing automatic devices to start and switch the motor and generator, such as are coming into successful use for direct-current synchronous converters, waterwheel generators and other rotating apparatus.

This disadvantage, moreover, largely disappears when, as usually happens, a system of single-phase generation is connected to other systems through motor-generator sets for interchange of power.

No. 4 is in general respects the same as No. 2 with the addition of a relatively new development known as the "phase converter" which preserves the balance of the system even when large blocks of single-phase power are taken from the system. Its use greatly extends the possibility of connecting single-phase loads directly to a polyphase system provided the frequency does not have to be changed.

The use of phase converters is relatively recent and perhaps not very well understood. This makes it of interest to discuss the method of balancing and the apparatus employed more in detail.

THEORY OF PHASE CONVERSION

The earliest known form of phase conversion is splitting the phase by inductance and capacity. In this case the energy of one phase is stored for a fraction of a cycle and released again so as to make the same energy active in another phase. All methods of phase conversion, therefor, involve the storage of energy. Even the phase conversion of wattless currents necessarily involves storage of energy. The expression "wattless energy" is not such a contradiction as it has sometimes been claimed to be. When energy is wattless it means that the energy delivered during one portion of a half cycle is returned during the other portion of the same half cycle; therefore the average energy flow is zero. But at the same time, we must not forget that even if a current is completely wattless, there is a real energy flow in both directions. Thus if we wish to change the phase of the current, whether energy current or wattless current, we must provide means for storing the momentary energy flow for a time corresponding to the change of phase that is to be effected.

The method of storing energy in inductances and condensers is very convenient for high-frequency currents but has not up to the present found much practical application for low-frequency power current. There is, therefore, for phase conversion on a large scale, only one type of apparatus that can be considered, a rotating machine which stores the energy in the mechanical inertia of the rotor.

In order to arrive at an understanding of the physical functions of phase conversion with a rotating machine, several different points of view are possible, as sometimes one and sometimes another is more helpful in arriving at direct conclusions. The following three methods of looking at the problem may be helpful:

I—PHASE CONVERTER CONSIDERED AS A MOTOR-GENERATOR

The phase converter is built as a quarter-phase induction motor or synchronous motor with a squirrel cage; one phase is a motor phase and the other phase is a generator phase. The input of the motor phase is equal to the output from the generator phase, not only in the average value of the power flow but in the instantaneous value of energy flow which is delivered and returned during the same half cycle. The only difference between the energy flow in the two phase windings of the converter is that the momentary values of current, volts and energy is delayed ¼ cycle in one winding in relation to the other. The squirrel cage is the medium for the transfer of energy, and the mechanical mass of the rotor provides the energy storage. In order to make it possible to store the energy in the rotor, there must be corresponding changes of speed and therefore the rotor must go through a cycle of speed change during each half cycle of the alternating current flow. This speed change of the rotor is evidenced by the vibration which is a characteristic of any single-phase machine. The speed change of the rotor has, however, nothing to do with the electrical functions of the machine in performing as a phase converter. If we could couple the rotor to a flywheel of infinite weight so that the speed change would be zero, the converter would perform in the same way.

Having thus explained how it is conceivable that the phase converter operates as a motor generator, it remains to explain what means are provided for making it perform in this way; in other words, what causes the energy flow in the two phases to vary the same cycle of momentary values although delayed ¼ cycle in time. Various means can be provided for producing the desired energy flow and will lead to different types of phase converters. Broadly, it can be stated that whatever means are provided, the result of these means must be the desired flow of currents through the windings, and therefore the means must consist in providing the necessary electromotive forces to cause these currents to flow through the windings.

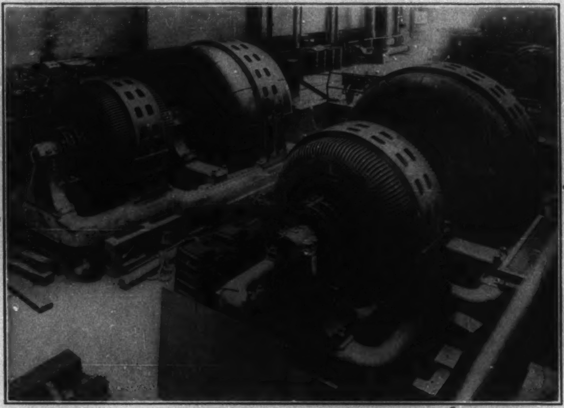
One method of providing these electromotive forces is to use an auxiliary generator which impresses the desired electromotive force on the windings. Instead of a generator any other convenient source of electromotive force may be used, such as a transformer or an induction regulator. Another method is to connect the windings of the converter with reference to the source of power and the load, in such a way that the electromotive forces are furnished automatically by the source of power.

The first method leads to the phase converter connected in shunt to the line and is the type that has been adopted in the phase balancer sets of the Philadelphia Electric Company; for the sake of brevity this type may be referred to as the shunt converter. The function of the shunt converter is to transfer energy from one phase to another in a polyphase system so as to neutralize the effect of single-phase load drawn from the same system in another place. The second method of producing the desired flow of current in the system leads to the series converter. In this type of converter the single-phase circuit is in series with one phase of the converter. The series converter, as applied for changing from single-phase power to polyphase power is described in a paper by one of the authors in 1911. This same arrangement is well adapted for change of polyphase to single-phase power and this method is in some cases preferable to the shunt converter. The function of the series converter is not to correct for a single-phase load that has been placed on a polyphase line but to change the single-phase load into a polyphase load before it is connected to the line.

II—The Phase Converter Considered as a Polyphase Generator

This second point of view is more artificial than the first but is more helpful in analyzing the function of the phase converter. For the purpose of such analyzing, a well-known mathematical artifice is made use of. A single-phase current can be considered as resolved into two polyphase components with opposite phase rotation. One of these polyphase components has the same phase rotation as a power system and constitutes

PLATE LXXIII.
A. I. E. E.
VOL. XXXV. 1916



[ALEXANDERSON AND HILL]

FIG. 1—PHASE BALANCER SETS

a legitimate load on the power system. The other component, which has the opposite phase rotation, is the one that causes the unbalancing of voltage, heating of generators and motors connected to the system, etc. The function of the phase converter is to neutralize this component of the single-phase load which has opposite phase rotation. From these considerations, it becomes evident how the phase balancing can be accomplished. This function consists in providing a machine which feeds into the system a polyphase current which has opposite phase rotation to the system, and is equal and opposite to the component of the single-phase load we wish to neturalize. It is now evident how the phase balancer ought to be constructed. The converter should be a polyphase machine, not necessarily synchronous, but preferably so in order not to draw lagging current from the system, and means are to be provided for forcing a current to flow through the windings of the phase machine which has opposite phase rotation to the system. The currents of opposite phase rotation are to be regulated in magnitude and phase corresponding to the single-phase load. One convenient way of producing such adjustable polyphase currents is to provide a polyphase generator with its field controlled by suitable regulators. These considerations lead to the design of the shunt converter with direct connected balancer and regulators such as used by the Philadelphia Electric Company. The construction of these phase balancers is illustrated in Fig. 1. The sets consist of a main converter and an auxiliary balancing machine which is controlled by automatic regulators. The main converter is mechanically connected to a generator which is called a balancer. The function of this balancer is to circulate polyphase currents of the desired phase and magnitude in the windings of the converter. This auxiliary generator is small compared to the converter because its output is used only to overcome the losses and inductive drop in the windings of the main converter.

III—The Phase Converter Considered as a Transformer

This point of view is also more artificial than the first one but it is helpful in understanding and analyzing the functions of the series converter. The two stator windings of the phase converter are considered as the primary and secondary of a transformer. The squirrel-cage rotor is a medium for transferring the current from the primary to the secondary and the characteristics of the phase converter as a transformer differs from the ordinary transformer only by the fact that the time phase of the secondary is ¼ cycle from the time phase of the primary. This displacement of time phase is due to the time required for the squirrel cage to rotate through the angle corresponding to the location of the primary and secondary windings of the stator. The function of the series converter is easiest explained in connection with a quarter-phase system, but it is obvious that it can be used in a three-phase system by the use of a Scott transformer connection. The object in the use of the converter is to distribute the single-phase load equally in the two phases of the quarter-phase system. If the problem were to distribute the single-phase load in two circuits of a single-phase system, it is easy to see how this could be done by the use of a series transformer. The single-phase load might be put directly in series with one circuit through the intermediate of a series transformer. If this transformer has a ratio of 1:1, the current would be equally distributed on the two circuits at all loads. The two phases of the quarter-phase system differ from the two circuits of the single-phase system for our present purpose only by the relative time phase. However, if the phase converter may be used as a transformer which changes the time phase of the current between its primary and its secondary to the desired degree, it can be used as a series transformer between the single-phase load circuit and one of the phases of the quarter-phase system in the same way and with the same characteristics as stated above with reference to the ordinary series transformer used to distribute the load on two circuits of the single-phase system. Carrying the analogy between the phase converter and the transformer still further, we can trace the source of the electromotive force required to force equal and opposite currents to flow in the primary and secondary windings. This electromotive force is derived directly from the primary circuit. To cause a current to flow through a winding requires a voltage and this voltage is evidenced by the impedance drop in the winding. From the theory of transformation, we have become in the habit of regarding the impedance of the primary and secondary windings of a transformer as a single impedance, which for the sake of convenience can be said to be located in either the secondary or primary windings. In either case we assume that a certain amount of the primary voltage is used up to overcome the impedance drop of the transformer windings. This impedance drop is evidenced by the voltage drop on the terminals of the secondary winding. The same considerations apply to the use of the converter as a series transformer. The ratio of current transformation is for all practical purposes constant at all loads at which the transformer can be used. The voltage drop on the secondary side is the sum of the impedance drop in the primary and secondary winding. In the case of the phase converter, the impedance drop includes the drop in the squirrel cage which is the transfer medium. However, we are also in the habit of measuring the impedance of the induction motor windings on the primary side and look upon the impedance in the stator and the rotor as concentrated in the stator winding. We therefore find that the impedance of a converter when considered as a transformer is the same as the stationary impedance of the same machine measured as an induction motor at standstill. From this analogue, we have a right to expect the following characteristics of the series converter and these conclusions are in entire agreement with practical measurements. The change of a single-phase load into polyphase load is automatic and results in a *perfect distribution of current in the two phases at all loads.* The voltage delivered to the single-phase circuit has a slight drop with increasing load and has the same characteristics with reference to current and power factor that would be obtained by placing an impedance in series with the single-phase circuit equal to the impedance of the windings of the converter.

APPLICATIONS OF PHASE CONVERTER

In regard to efficiency and size, the phase converter can be considered as being in the same class as the synchronous condenser. In fact it has substantially the same structure, the difference being that the squirrel cage which is usually employed in the synchronous condensers to counteract hunting becomes in the phase converter the main rotor winding, while the field winding of the synchronous condenser is reduced to a small winding sufficient to carry no-load excitation. Due to the similarity in structure the same machine can act as a synchronous condenser and phase converter at the same time if the windings are proportioned for this purpose. The fact that the machines can be designed so that they are useful as synchronous condensers and phase converters simultaneously is worth consideration in the application of the methods of phase conversion, as several methods of application are possible. In the first place, it is possible to place the phase converters either in the power house or at any desired place of the distribution system. Synchronous condensers may be needed on distribution systems for the sake of counteracting low power factor, and such synchronous condensers can, if desired, be designed so that they can in addition be used as phase balancers, in order to make it possible to draw single-phase load from the same system. If, on the other hand, the main load is synchronous converters with unity or leading power factor it may be more practical to locate the phase balancers in the power stations. The single-phase load is usually of low power factor and the lagging current of the single-phase system may be furnished either to the single-phase distribution system by single-phase synchronous condensers or may be furnished in the power house by polyphase machinery after the whole kilovolt-amperes of the single-phase load has been converted to polyphase. In the latter case, the phase converter can be used for power factor correction as well as phase conversion, but in that case it must be large enough to convert the whole single-phase-kilovolt amperes at a low power factor and then furnish polyphase current to correct for this power factor; whereas in the other case where the single-phase power factor is corrected for by synchronous condensers the phase converter needs to convert only the power component of the single-phase load. The choice between these methods of conversion will depend upon local conditions of expediency.

The shunt converter is of particular value in those cases when it is expected that single-phase load may be drawn from different phases of a polyphase system. In such cases unbalancing of the single-phase load will be partly neutralized and it will be necessary to convert only the difference between the single-phase loads. There are, on the other hand, cases where the series phase converter can be used to best advantage. Those are cases when it is desired to convert the single-phase load at the point where it is connected to the polyphase system. The series converter has in that case the advantage of simplicity, as the arrangement is automatic and no auxiliary generator or voltage regulator is needed. In cases where a single electric welding machine or arc furnace is to be fed from a polyphase system, the series converter should be recommended. If such an installation has been made with a series converter in order to insure the lowest first cost and it should be desired to add other furnaces to the other phases, the same converter might be used as a shunt converter without any increase of converter capacity but with the addition of suitable regulating devices.

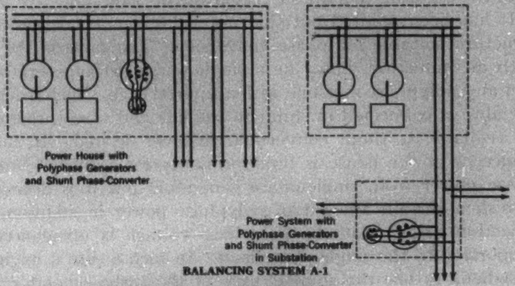
It has been pointed out that a synchronous condenser has a structure suitable for phase conversion. The same is the case with an induction motor or a single-phase turbo-generator, in fact any polyphase machine with a squirrel cage. Such machines are always connected in shunt to the line and would, therefore, be available as shunt converters wherever desired. If, for instance, a power house is built primarily for furnishing single-phase power from single-phase generators but it is desired to furnish a certain amount of polyphase power in addition, the objection arises that the polyphase voltage is unbalanced in proportion to the single-phase load. In such a case it might be expedient to use the squirrel cage of the turbo-generator as a converter medium by adding suitable regulating devices. The interchange of current between the phases is then already determined by the load conditions, but the electromotive forces necessary to cause this interchange of current appear in the unbalancing of the line voltage. This unbalancing of voltages can be treated with the same method of analysis as given in the preceding for the unbalancing of current. The unbalancing electromotive forces are resolved into their components and the correcting electromotive force may be furnished by a generator driven either from the turbine shafts or by a synchronous motor. This generator has the same character and functions as the auxiliary balancing generator in the phase-converter set. A power house for mixed single-phase and polyphase load equipped in this way can be operated in multiple with other power houses using standard polyphase generators.

The methods that may be employed in order to equip a power system so that it can take on mixed single-phase and polyphase load can be classified in the following groups:

A. The use of standard polyphase generators and phase converters for correcting the unbalanced load. The phase converters may be placed either in the power station or substations and may be

1. shunt converters, or
2. series converters.

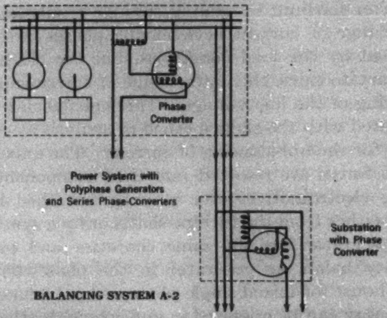
B. The use of special generators with squirrel-cage windings, adapted for mixed single-phase and polyphase load, and an equipment of automatic apparatus to prevent the unbalancing of voltage that the single-phase load tends to produce.



Power House with Polyphase Generators and Shunt Phase-Converter

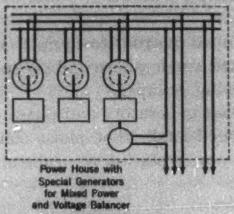
Power System with Polyphase Generators and Shunt Phase-Converter in Substation

BALANCING SYSTEM A-1


Phase
Converter
Substation
with Phase
Converter

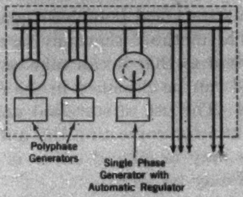
Power System with Polyphase Generators and Series Phase-Converters

BALANCING SYSTEM A-2



Power House with Special Generators for Mixed Power and Voltage Balancer

BALANCING SYSTEM B


Polyphase
Generators
Single Phase
Generator with
Automatic Regulator

BALANCING SYSTEM C

C. The use of standard polyphase generators and special single-phase generators connected to the same bus bars with automatic means for regulating the governors and fields of the single-phase generators so that they will absorb the entire unbalancing of the current.

The choice between these three methods of balancing a power system with mixed load will depend upon local conditions and general expedience. All three methods have the advantage of avoiding duplication of the transformation and distribution system. The first method involving the use of the phase converter introduces the least change in standard polyphase power systems and is adapted for the cases where the polyphase load is predominant. The second method is adapted for cases where the single-phase load is predominant, and has the merit of making all of the generating units available for both single and polyphase power as the system may demand. It is thus adaptable to growth and changes in the system, to preservation of good load factor and interconnection with other power systems. The third method does not offer any particular advantages over the two others but is mentioned for the sake of completeness. Its use might be considered in cases where single-phase and polyphase generators are already in use in the same power house and it is desired to use the polyphase distribution system for taking on single-phase load. The efficiency of all three methods may be said as a whole to be on a par. In specific cases some slight advantage may be figured out for each of the systems, but the determining factors will not be so much inherent efficiency of the electrical apparatus as the difference in load factors and the influence of load factors on steam economy.

For the sake of an easy comparison of the different methods proposed, a tabulated set of diagrams are given showing the essential features of each system.

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SINGLE-PHASE POWER SERVICE FROM CENTRAL STATIONS

BY R. E. GILMAN AND C. LE G. FORTESCUE

ABSTRACT OF PAPER

The purpose of the paper is to outline several methods by which single-phase power may be supplied from a polyphase system and to discuss their advantages and disadvantages.

The unbalance in voltage when single-phase power is supplied direct from a polyphase circuit is explained. The law of distribution of load in the polyphase system is deduced, and the limitations of this method of supplying single-phase power are discussed.

Single-phase generation is one solution of the problem, motor or steam drive may be used depending on the size of unit required. An outline of the theory of the single-phase generator is given from different points of view.

The essential requirements for phase balancing are deduced from which an outline of the theory of phase balancing is developed. Attention is called to the requirements of the control apparatus. The behavior of the balancer under short circuit is given consideration.

The merits of single-phase generation and phase balancing in the case of a single-phase load from one phase are discussed, with the conclusion that there is little difference in cost between the two schemes and there is much to be said in favor of single-phase generation for such a case.

INTRODUCTION

IT IS the purpose of this paper to outline several methods by which a power company may supply single-phase power, to indicate under what conditions each method may be considered as the most suitable, and to explain, from more than one viewpoint, some of the features of the design and theory of the apparatus required.

Central stations with polyphase equipment are often called upon to supply single-phase loads in small quantities. In general, this is attended with no difficulty, as the individual loads are ordinarily small and a combination of a large number of small loads ordinarily results in a fairly balanced total load. Under certain circumstances, however, even with relatively small single-phase loads, it would be desirable to balance up individual feeders if it were possible to obtain the necessary apparatus.

When, however, the individual single-phase loads become relatively large, compared with the total capacity of the station, both the voltage and current unbalance of the system resulting, may cause serious inconvenience and it becomes necessary to provide special means for handling these loads.

It is proposed to consider the problem under the following heads.

1. Single-phase loads supplied direct from the polyphase system.
2. Single-phase loads supplied from separate single-phase generators.
3. Single-phase loads supplied from polyphase system direct, but the balance of the system maintained by means of auxiliary apparatus.

I—SINGLE-PHASE LOADS SUPPLIED DIRECT FROM THE POLYPHASE SYSTEM

When a single-phase load is supplied direct from any polyphase generator, the effect of this load is to produce an unbalance in the terminal voltage of the machine. The voltage of any phase of a generator when carrying load is the resultant of the induced voltage and the e.m.f. necessary to force the current against the impedance of the phase winding. It is evident, therefore, that if equal currents of the same displacement are supplied by all phases, in other words, balanced load is delivered by the machine, that the terminal voltage diagram is similar to the no-load voltage diagram, but that all e.m.fs. are rotated through the same angle; balanced voltages are therefore maintained. If, however, a single-phase load is applied to the machine (for example in the case of a three-phase generator), the terminal voltages of two legs only are affected by the load current and the resultant triangle of terminal voltages is distorted from an equilateral or balanced triangle. See Figs. 1 and 2.

The division of an unbalanced load between the various machines connected to a polyphase system may be explained as follows: The distortion of the e.m.f. diagram must be the same for all generators connected to common bus bars and for all feeders leaving these bus bars, therefore, the magnitude of the impedance drop in the machines is identical for all units. In other words, the unbalance in load distributes itself between all machines connected to the system inversely in proportion to the impedance of the machine plus the impedance of the line circuit up to the point of application of the unbalanced load.

The magnitude of the voltage unbalancing in any system will depend, therefore, upon the relative amount of balanced load as compared with the unbalanced portion. In particular, symmetrical polyphase machinery, such as synchronous motors, synchronous converters or induction motors, will have a pronounced balancing effect on the system independent of the amount of load carried by them.

In addition to the voltage unbalance, single-phase loads on polyphase systems may produce undesirable temperatures in certain portions of the polyphase apparatus unless such apparatus is specially designed to carry unbalanced loads. A full explanation of this phenomenon will be given under the discussion on single-phase generators and phase balancing apparatus.

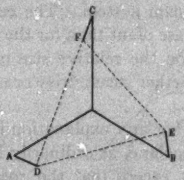

FIG. 1.—CHANGE IN VOLTAGE TRIANGLE DUE TO BALANCED LOAD

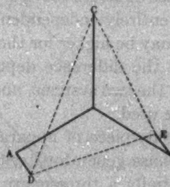

FIG 2.—CHANGE IN VOLTAGE TRIANGLE DUE TO SINGLE-PHASE LOAD

When the unbalance in voltage, or the heating of polyphase machines become excessive to such an extent that the service is in danger, some other means must be considered for supplying the unbalanced loads. The two means, which at once suggest themselves, are the use of separate single-phase generators, or the use of auxiliary apparatus to restore the balance.

In considering these two subjects, two general methods of analysis present themselves. The polyphase generator may be considered as a combination of single-phase generators, or the single-phase generator may be considered as a special case of loading of the polyphase generator. The problem will be presented from both points of view in the following discussion of the action of the single-phase generator and the general problem of phase balancing.

II—SINGLE-PHASE LOADS SUPPLIED FROM SEPARATE SINGLE-PHASE GENERATORS

If the single-phase load supplied, is of a different frequency from that of the polyphase system, it is obvious that a single-phase generator is the only logical solution. This generator may be driven either by steam direct, or by a motor connected to the polyphase system. If the frequency of the single-phase load is the same as that of the polyphase system, and it is decided to generate this load as single-phase power, the generators may be driven by motor, if the load is a small percentage of the total station capacity; or they may be steam driven, if the generators are of sufficient output to warrant it. Choice of the drive is largely one of dollars and cents, to be determined by the cost of the plant and the economy of operation. The main advantage in the use of steam drive is that the single-phase load of the station is entirely independent of the main system. The cost of power may be higher for the single-phase plant than for the main system, the difference depending upon the relative size of the units in the two systems, and upon whether steam drive or motor drive be used.

The only piece of apparatus requiring any explanation is the single-phase generator itself. This machine, as ordinarily built, is essentially a three-phase generator, except that the rotor is provided with a damper or a squirrel-cage winding in the faces of the field poles. The general construction and appearance of such dampers is well known, as their use is quite common in connection with different types of synchronous apparatus. In a self-starting synchronous motor, dampers are employed to increase the torque per ampere at starting, and in synchronous converters to prevent phase swinging or hunting from becoming excessive, while in single-phase machines dampers provide a low resistance, a low reactance path for currents induced in the rotor to compensate for the pulsating armature reaction.

The first requisite of any constant-potential machine is that the m.m.f. of the load circuit must not change the main flux of the machine, so long as the load is constant. In single-phase generators, therefore, where the m.m.f. of the load circuit is pulsating, that is, variable in magnitude from one instant to the next, and in position, with respect to the exciting circuit, also from one instant to the next, it is obvious that some other m.m.f. exists of such value at all instants, as to produce, in combination with the load reaction, a m.m.f. of constant value and fixed in position with respect to the main poles. This m.m.f. is supplied by currents which are induced in the damper winding.

A complete discussion going into the calculation of these currents is not warranted in this paper, but it may not be out of place to give an illustration of the underlying principle based upon the well known mathematical theorem that two vectors of equal value, rotating in opposite direction at equal angular velocity, produce a sine wave. The diagrams shown in Fig. 3 are drawn under the assumption that the m.m.f. distribution of the armature winding is a sine wave. A little consideration will show that if these damper currents are not of sufficient magnitude to completely neutralize the pulsating component of the armature, the main flux must pulsate at double frequency. Also, that if the resistance to the flow of these currents is high ,

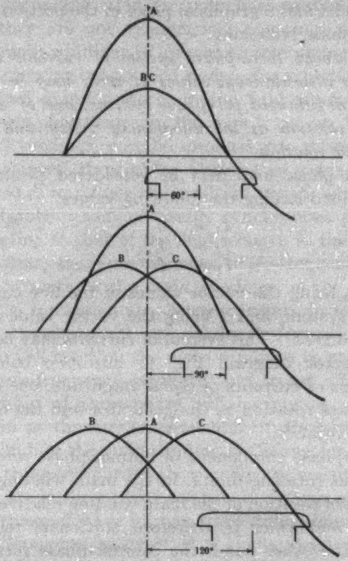

FIG. 3.—A = M.M.F. DISTRIBUTION DUE TO LOAD CURRENT.
B, C = VECTOR COMPONENTS OF A OF OPPOSITE ROTATION.

excessive losses may occur in the pole faces of the machine. This latter phenomenon explains the temperature rise which occurs in polyphase machines without dampers when carrying unbalanced loads.

There are some advantages in considering the single-phase generator from the point of view of a polyphase machine having an unbalanced load. It will be necessary, first of all, to accept the following theorem, the mathematical proof of which is given in the appendix and a graphical proof in the portion of this paper devoted to phase balancing.

Any unbalanced three-phase system of currents or e.m.f's, the sum of whose instantaneous values is zero, may be resolved into two component balanced polyphase systems, one of which has the same phase rotation as the unbalanced system and the other has opposite phase rotation.

The single-phase load may be considered as an unbalanced three-phase load having the following values.

$$I_1 = 0$$
$$I_2 = I$$
$$I_3 = -I$$

I_1, I_2 and I_3 being the vector values of the line currents of the three-phase system, and I being the vector value of the single-phase load current. This system of currents may be resolved as shown in vector diagram Fig. 9, into two balanced three-phase systems of currents of equal amplitude, one of which has the same phase rotation as the generator and the other has opposite phase rotation.

The three-phase component of normal phase rotation sets up a synchronous rotating m.m.f. in the main winding opposite to the direction of rotation of the main winding relative to the damper winding and which is, therefore, stationary relative to the latter. On the other hand, the counter-phase rotational component sets up a synchronous rotating m.m.f. which has the same direction of rotation as that of the main winding relative to the damper windings, and, therefore, the field set up by it cuts the latter at double synchronous speed, and induces in them double frequency polyphase currents, which produce a rotating counter m.m.f. approximate in value to the m.m.f. set up by the counter-phase rotational component of current in the main winding; the degree of approximation being proportionate to the closeness of magnetic coupling between the two windings. If it were possible to make the magnetic coupling perfect, and if the damper resistance were zero, no magnetic flux would be set up by the counter-phase rotational component and, therefore, the unbalancing in the terminal e.m.f. would be due only to the $I R$ drop in the main windings.

When the dampers are perfect, the exciting field winding and the pole faces will have no currents induced in them, but since it is not possible to obtain absolute perfection in this respect, a minute amount of double-frequency current will be set up in the pole faces and exciting circuit. In machines without dampers such as are commonly used for polyphase systems, these circuits, since they are not symmetrical polyphase circuits, will react on the main windings in an undesirable manner, when the machines are carrying unbalanced loads. For example, a counter-phase rotational m.m.f. induces in the field winding a double-frequency single-phase current, the m.m.f. set up by which in the main field windings, may be resolved into those due to two equivalent balanced three-phase systems of currents, one of which reacts so as to reduce the resultant m.m.f. while the other sets up a rotating m.m.f. of double synchronous speed in the opposite direction to that of the field relative to the main windings. The latter, therefore, induces triple-frequency balanced three-phase currents in the main windings, of the same phase rotation as the fundamental. These currents in turn react on the exciting circuit to set up quadruple-frequency currents, which in turn will react on the main windings to produce three-phase quintuple-frequency currents, and so on. The result is a complete train of three-phase odd harmonics of the same phase rotation as the fundamental and of diminishing amplitude in the e.m.f. of the main winding of the machine. One particular set of these odd harmonics, namely the multiples of three, because they are in three-phase relation in a three-phase system, will produce unequal wave forms on the three phases.

From the foregoing analysis of a single-phase generator, it appears that the single-phase impedance is made up of two elements, namely, the effective impedance of the generator considered as a polyphase machine to the symmetrical three-phase positive rotational component of the load, and its effective impedance to the negative rotational component of the load. The former is the impedance of the machine to a symmetrical polyphase current of positive phase rotation (the positive rotation being assumed to be that of the generator), when the machine is running in the normal direction at synchronous speed *with zero excitation.* The latter is the impedance of the machine to a symmetrical polyphase current of negative phase rotation when the machine is running in the normal direction at synchronous speed *with zero excitation*. The former of these quantities is dependent, in some degree, upon the saturation of the magnetic circuit, but corrections can be made from the no-load saturation curves of a machine for any desired degree of approximation. The latter value is only slightly affected by saturation, especially where the damper design is effective.

The single-phase impedance is the sum of the two impedances between neutral point and terminals, obtained in the manner described in the last paragraph, combined as complex quantities.

The effect of the dampers on short circuit is not to increase the transient value, but to sustain it. Therefore, the severity of a short circuit on a machine provided with dampers is not increased, from the magnetic standpoint, but the action continues for a longer period.

It will be obvious from the preceding discussion that the single-phase generator may also be used as a polyphase generator, if so designed, and will be of superior type to the standard polyphase machine, especially where the polyphase load is liable to be unbalanced. When installing single-phase steam-driven generators, the possibility of using them as auxiliaries for the polyphase system may be worthy of consideration. This would be particularly the case if the peaks of the single-phase and polyphase systems occur at different periods.

III—SINGLE-PHASE LOADS SUPPLIED FROM POLYPHASE SYSTEM DIRECT, BUT THE BALANCE OF THE SYSTEM MAINTAINED BY MEANS OF AUXILIARY APPARATUS

It has already been shown that any unbalanced single-phase loads will be distributed among the various machines connected to the system in inverse ratio to the impedance of the machine and the circuit up to the point of unbalance. From this consideration it is apparent that if a machine of zero impedance were connected to the system, all of the unbalanced load would be assumed by this unit. Therefore, to produce a balancer, it is only necessary to neutralize the impedance drop due to the unbalanced load. It is possible to produce the equivalent of zero impedance by introducing one or more single-phase boosters supplying a voltage of the proper magnitude and phase position so that the distorted triangle of voltages will be restored to a balanced or equilateral triangle.

It is evident that if a motor, having balanced symmetrical counter e.m.f., is connected to a balanced three-phase system it will absorb balanced load from the system. If all unbalanced loads were isolated and carried by one generator, it is obvious, as explained before, that the voltage of this generator would become unbalanced. For example, see Fig. 4. The problem now is how to connect this unit to the balanced system, without permitting any of the unbalanced load to be carried from the main generator. It is evident that by adjusting the excitation of this generator, so that the terminal e.m.f. of any phase, for example *A B*, is equal to that of the polyphase system, and if, in series with the terminal *C* a single-phase booster be connected giving an e.m.f. equal to *C D* and of the direction shown in the figure, a balanced voltage triangle can be produced equal to that of the main system and, if this machine be paralleled with the main system, no redistribution of load will occur. If this generator and booster were driven from the same shaft, it would be possible to remove the driving power and the combined unit would act as a motor-generator taking balanced polyphase power from the system and delivering single-phase energy as a generator. A balancer has, therefore, been produced which will function properly so long as the unbalanced load remains fixed in magnitude and phase. If the phase of the single-phase load should change, it is necessary to change the phase of the booster with respect to the balancer and if the magnitude of the load should change it will be necessary to change the amount of booster in proportion. In the diagram shown, the resultant

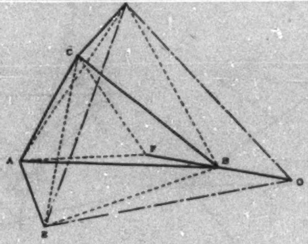

FIG. 4

single-phase load is carried across terminals *AC*, and it is readily seen that if the load should be transferred to terminals *AB*, or *BC* the booster would have to be shifted in direction 120 deg. and 240 deg. respectively.

It is also possible to start from any other side of the triangle and by constructing equilateral triangles with these sides as a base, two other boosts are obtained, which can also produce the necessary balance.

It is evident, therefore, that in place of any one of these three boosts, such for example as *C D*, two boosts of equal voltage and 180 deg. phase displacement can be used if these boosters are connected to points *A* and *B* of the triangle. See Fig. 5. Or three boosters can be used, one connected to each corner of the original triangle. From Fig. 4, it will be seen that triangles *C D B* and *A E B* are similar and equal and since by construction the sides *C B* and *E B* are 60 deg. apart, the sides *C D* and *A E* are 60 deg. apart and the e.m.fs. *C D*, *A E* and *F B* are 120 deg. apart and all equal in magnitude. If any of these values be reversed, it is readily shown that all three boosts can be employed to produce a balanced triangle. It would then be possible to combine all three booster windings on a single armature, which would be wound exactly like a three-phase machine except that the phase displacement of the terminal voltages would be 60 deg. in place of 120 deg. See triangle *D E G*, Fig. 4.

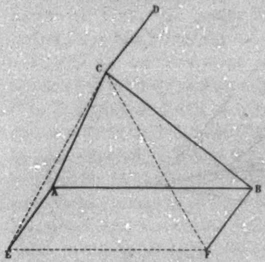

FIG. 5.

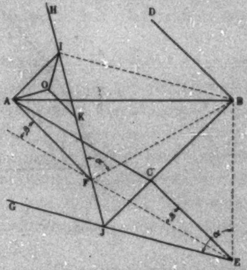

FIG. 6.

If starting out with the triangle *A B C*, an equilateral triangle be constructed with *A C* as a base, the boost *B D* can be replaced by two boosts *A F* and *C E*, and the equivalent equilateral triangle *B E F* will be obtained. If from point *E* a line *E G* be drawn at 30 deg. to the line CE, and from point F the line FH be drawn at 30 deg., it is apparent from the figure that with B as an apex a series of equilateral triangles can be formed by measuring equal distances from points E and F respectively along the lines GE and FH.

One case, which is of particular interest, is when the two boosts become parallel as shown in Fig. 6. In this case the boosts are at right angles to the line DB and this at once suggests the possibility of replacing them by a balanced three-phase system as indicated by the triangle AIK. It has been shown by the construction that triangle BIJ is equilateral and it is self evident that if IO, AO and KO be combined successively with IB, IJ and JB that an equilateral triangle would be obtained, as shown by OLM, Fig. 7. Also, the construction shows that AO, CM and LB drawn from points A, B and C produce the same triangle.

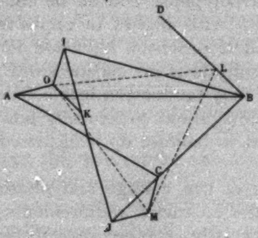

FIG. 7.

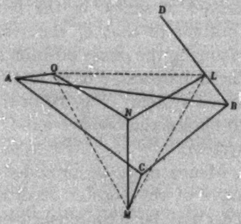

FIG. 8.

It is to be noted that AO, CM and LB are all respectively equal to one-third of the length BD. Also that these three boosts form a balanced three-phase system, and combine with AB, BC and CA to produce an equilateral triangle with opposite phase rotations.

It has been shown graphically, step by step, how any unbalanced triangle of voltages can be forced to a balanced triangle by various combinations of single-phase boosters using one, two or three boosters to accomplish this purpose. The solution shown in Fig. 7, is the most general for the three-phase system, and can be stated as follows: Any unbalanced triangle of voltages in a three-phase system can be replaced by two balanced systems of the proper magnitude and combined at the correct phase angle. In order to simplify matters, the graphic demonstration of this fact has been confined to the case of the three-phase system. It is shown, however, in the appendix to this paper, that the above solution of unbalance is perfectly general.

Given an unbalanced triangle, as shown in Fig. 8, the graphic solution is indicated.

In an extensive polyphase system, it frequently happens that while the aggregate single-phase loads produce fairly balanced polyphase load at the central station bus bars, the voltage at the ends of individual feeders may be considerably unbalanced. It is proved in the appendix that an unbalanced polyphase e.m.f. can be resolved into two balanced polyphase e.m.fs., one of which is of opposite phase rotation to that of the system. If, therefore, at a distributing point, a polyphase booster be connected in series, in the feeder lines, with phases in opposite rotation to that of the system, and if provision be made for changing the phase position and magnitude of the booster e.m.f., the unbalanced e.m.fs. at this point may be boosted into a balanced system. Fig. 10 in the appendix, shows graphically how to obtain the booster e.m.f. required to balance up a distorted system.

Means must be provided to control the voltage and phase angle of the booster according to the balancing requirements. This may be accomplished by two specially arranged regulators, the arrangement of which will depend upon the methods used to adjust phase and voltage in the booster.

Where both current and voltage are seriously unbalanced, the auxiliary apparatus must be such as to supply the elements necessary to produce balance in both voltage and current. It has already been pointed out that when an unbalanced load is supplied from a polyphase system, all the polyphase rotating machinery connected to the system tend to keep the voltages in balance and supply current in such a manner as to approach a condition of balance at the bus bars. The particular element of an unbalanced load that must be supplied in order to maintain a balanced load at the bus bars, is the counter-phase rotational symmetrical polyphase component of the load.

The impedance of a dynamo electric machine to counter-phase rotational symmetrical polyphase currents may be made extremely low by the addition of carefully designed polyphase dampers or squirrel-cage windings. If, in addition, auxiliary means be provided, externally or internally, to assist the natural action of the machine as a balancer, its admittance to the counter-phase rotational currents may be made infinite, so that the terminal e.m.f. of the machine will be absolutely balanced no matter how much counter-rotational current it may be called upon to supply.

The ability of an unassisted dynamo electric machine to act as a balancer is measured by its impedance to the counter-phase rotational component of the unbalanced load. The action of such a machine, when thrown on to an unbalanced system, consists in supplying such an amount of this counter-phase rotational component as will be necessary to pull the system and the machine into the same degree of unbalance. The voltage balance of the system is thereby improved at the expense of the voltage balance of the machine. The voltages that cause unbalance at the machine terminals are the impedance drops due to the counter-phase rotational current supplied by the machine, and are, therefore, counter-phase rotational and symmetrical. One way, therefore, for assisting the machine to maintain a balance, is to supply an equal and opposite counter-phase rotational e.m.f. in series with the windings by means of a booster, and this will render the effective impedance of the machine to these currents zero.

Since with varying degrees and phases of unbalance the impedance e.m.f. will vary in degree and phase position, the external source of e.m.f. must be provided with similar adjustment in voltage and phase position, and the apparatus provided to control these adjustments must respond to the variations of unbalance in the proper degree. The means of adjustment for an auxiliary machine connected rigidly to the main machine may consist of two field windings in quadrature relation, connected to separate exciters. This will permit of adjustment both in magnitude and phase position of the auxiliary machine in respect to the main machine.

The control of the adjustment of the auxiliary machine, with various degrees and phases of unbalancing, is not a simple problem, and until it has been satisfactorily solved, a perfect phase balancer cannot be considered as an accomplished fact. The essential requirements of the regulating apparatus are:

1. That it be extremely sensitive to voltage differences.

2. That it be capable of adjustment so that there will be no hunting between the control elements.

Whether these conditions have been obtained in any installation of balancers, up to the present time, is open to question.

Since a single-phase e.m.f. may be resolved into two balanced polyphase e.m.fs. of opposite phase rotation, perfect balance may be obtained by one single-phase booster in connection with the main machine. One component of this single-phase voltage must be the counter-phase rotational component required to balance up the terminal voltages of the main machine. The other component, which is of the same phase as the system, is provided for by the excitation of the main machine. The single-phase machine may be arranged so that its middle point is connected to the neutral of all but two of the windings of the main machine, its terminal being connected to the ends of the two remaining windings of the main machine, which would otherwise be connected to the common point, and it should be mounted on the same shaft as the main machine and be provided with means for changing voltage and phase with respect thereto.

The obvious defect of such a system lies in the difficulty of control, since with changing phase of unbalancing, the excitation of the main machine must be changed as well as that of the auxiliary single-phase booster.

A modified form of the same scheme would require a number of single-phase machines of the same phase, connected between the neutral point and each phase of the main machine, the complete set of machines being capable of simultaneous phase shifting, and each machine separately having full voltage control.

As a corollary to the above, it may be stated that any system of unbalanced polyphase e.m.fs. may be used as an auxiliary means of producing perfect phase balancing.

While some of the schemes outlined above may, with restricted phases of unbalancing, offer a satisfactory solution, the use of a polyphase main machine combined with a polyphase auxiliary machine is the simplest solution for the problem of general balancing and all practical balancers will be based upon this feature.

A convenient way of regarding the phase balancer is to consider it as a motor taking power symmetrically from the polyphase system and delivering it to the same system as single phase current. The motor and generator actions tend to counteract one another in any polyphase machine provided with dampers and when the auxiliary booster is added, the annulment is complete after the auxiliary has become adjusted.

The action of a balancer under short-circuit condition will, therefore, depend on the range of excitation of the auxiliary. For the initial condition, until the auxiliary has had time to adjust itself, the main machine will feed into the short circuit in much the same manner as any other synchronous machine provided with dampers. If the auxiliary had a range sufficient to give complete balance under short circuit, the full polyphase capacity of the system would be concentrated in the short circuit and the phase balancer would necessarily carry a counterphase rotational load of equal value. In other words, the current delivered by a perfect balancer under short-circuit condition, is limited only by the current that the system on which it is operating, can deliver to a symmetrical short circuit.

Practically the short-circuit conditions are not so bad as indicated in the above paragraphs, because the limitation in voltage of the auxiliary machine permits of perfect balancing only up to a certain point. The short-circuit stresses in the balancer will nevertheless be much more severe than such as would be obtained in a generator or synchronous condenser of the same size operating on the system.

Conclusion

Where the unbalanced load fluctuates between the different phases and is of sufficient magnitude to cause trouble, a phase balancer is clearly the proper solution of the problem.

When a single-phase load on one phase is to be supplied, the problem becomes one of relative economy and reliability in service of the balancer, as compared with the single-phase generator. The main machine of the balancer set must have the same polyphase output as the alternative single-phase machine, and must also be provided with dampers of equal rating; but it must also be capable of withstanding the more severe short-circuit conditions due to its balancing action. In the balancer there is very little torque on the shaft and, therefore, the mechanical design may be cheapened and the operating speed increased. It is doubtful, however, if the main machine of the balancer set can be made much cheaper than a single-phase machine of the same output.

The auxiliary machine will be necessarily costly on account of the double set of poles and the wide range of excitation required. Its exciters must be relatively large in capacity so as to provide rapid change in excitation from full positive to full negative. In addition there will be the control system, which is complicated and costly. It is questionable whether this portion of the balancer set can be made for much less cost than the motor required for the equivalent single-phase machine.

From an operating standpoint, there is much to be said in favor of single-phase generation. In the first place, it is isolated to a large extent, or, if steam driven, completely, from the main polyphase system. This is of distinct advantage if the single-phase load is subject to frequent and violent interruptions. In the second place, the short-circuit condition resulting from the use of the single-phase machine will be, in general, much less severe and, therefore, less apt to cause trouble and prolonged interruptions in service, than when a balancer is used.

From the point of view of economy of operation, there is little to be said in favor of one over the other; the balance is probably in favor of the phase balancer when compared with the motor-generator set, and in favor of the generator when it is steam driven.

APPENDIX

An unbalanced three-phase system, in which the sum of the instantaneous values of the elements is zero, can be resolved into two balanced systems of positive and negative phase rotation.

In a three-phase system let the positive and negative phase rotational systems be,—

$$\begin{aligned} E_1 &= E_1 & \qquad E_1' &= E_1' \\ E_2 &= \omega E_1 & \qquad E_2' &= \omega^2 E_1' \\ E_3 &= \omega^2 E_1 & \qquad E_3' &= \omega E_1' \end{aligned}$$

Where ω is one of the imaginary cube roots of unity. Then if Ea, Eb and Ec be the unbalanced e.m.f. such that,—

$$\begin{aligned} Ea &= E_1 + E_1' \\ Eb &= E_2 + E_2' \\ Ec &= E_3 + E_3' \end{aligned}$$

With the condition, $Ea + Eb + Ec = 0$, this set of equations is determinate and the symmetrical solutions for the balanced components are as follows,—

$$E_1 = \frac{Ea + \omega^2 Eb + \omega Ec}{3}, \qquad E_2 = \frac{Eb + \omega^2 Ec + \omega Ea}{3}$$

$$E_3 = \frac{Ec + \omega^2 Ec + \omega Eb}{3}$$

$$E_1' = \frac{Ea + \omega Eb + \omega^2 Ec}{3}, \qquad E_2' = \frac{Eb + \omega Ec + \omega^2 Ea}{3}$$

$$E_3' = \frac{Ec + \omega Ea + \omega^2 Eb}{3}$$

Applying these to a single-phase load on a three-phase system, if I_1 be the value of the current.

$$I_a = 0$$
$$I_b = I_0$$
$$I_c = -I_0$$

and, therefore,

$$I_1 = -j\,\frac{I_0}{\sqrt{3}},\; I_2 = \frac{3 + j\sqrt{3}}{6} I_0,\; I_3 = -\,\frac{3 - j\sqrt{3}}{6}\, I_0$$

$$I_1' = +j\,\frac{I_0}{\sqrt{3}},\; I_2' = \frac{3 - j\sqrt{3}}{6}\,,\; I_3' = -\,\frac{3 + j\sqrt{3}}{6}\, I_0$$

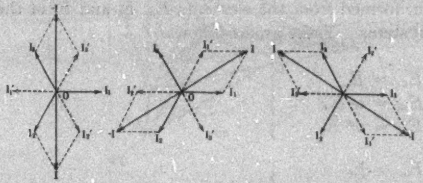

Fig. 9.—Single-Phase Load on Phases *A*, *B* and *C* Respectively Resolved into Two Balanced Three-Phase Components of Positive and Negative Phase Rotation.

Fig. 9 shows in a vector diagram the positive and negative phase rotational components of a single-phase load of equal magnitude and power factor on each phase of a three-phase system. The component of the same phase rotation as the system remains constant, while the counter-phase rotational component changes in phase through 120 deg. with each change in load position.

The formulas given above, may be interpreted as follows:

The negative phase rotational system is the mean of the three symmetrical systems obtained by taking each of the e.m.fs. E_a, E_b and E_c of the original system and considering it as a member of a balanced system. This results in the three systems:

$$\left.\begin{aligned} E_a &= E_a \\ E_{b1} &= \omega^2 E_a \\ E_c &= \omega E_a \end{aligned}\right\} \qquad (1)$$

$$\left.\begin{aligned} E_b &= E_b \\ E_{c2} &= \omega^2 E_b \\ E_{a1} &= \omega E_b \end{aligned}\right\} \qquad (2)$$

$$\left.\begin{aligned} E_c &= E_c \\ E_{a2} &= \omega^2 E_c \\ E_{b2} &= \omega E_c \end{aligned}\right\} \qquad (3)$$

from which the negative phase rotational component is obtained by taking the mean of the three quantities in the three groups having the same sub-letter.

Similarly the positive phase rotational component is obtained by taking the mean of three symmetrical systems of positive rotation, formed from the elements E_a, E_b and E_c of the unbalanced systems. These are as follows:

$$\left.\begin{aligned} E_a &= E_a \\ E_{b3} &= \omega E_a \\ E_{c3} &= \omega^2 E_a \end{aligned}\right\} \qquad (4)$$

$$\left.\begin{aligned} E_b &= E_b \\ E_{c4} &= \omega E_b \\ E_{a3} &= \omega^2 E_b \end{aligned}\right\} \qquad (5)$$

$$\left.\begin{aligned} E_c &= E_c \\ E_{a4} &= \omega E_c \\ E_{b4} &= \omega^2 E_c \end{aligned}\right\} \qquad (6)$$

Then, as before, each element of the component of positive phase rotation is obtained by taking out of each group the elements having the same sub-letter and finding their mean value.

Fig. 10 illustrates the graphical construction required to carry out the operations indicated above. The triangle A, B and C represents the unbalanced polyphase system which may also be represented by the vectors $O\,A$, $O\,B$ and $O\,C$ drawn from the centroid O of the triangle A, B and C. Two circles are described with O as center, namely $A\ C_1 C_3$ having $O\,A$ as radius, and $B\ C_2 C_4$ having $O\,B$ as radius. In the circle $A\ C_1 C_3$, $O\,C$ is taken 120 deg. in advance of $O\,A$ and, therefore, corresponds to $O\,C$ in the symmetrical system based on OA, having negative phase rotation. In the circle $B\ C_2\ C_4$, $O\ C_2$ lags 120 deg. behind OB and, therefore, corresponds to the vector OC in the symmetrical system of negative phase rotation based on OB. The corresponding vector $O3$ of the symmetrical negative phase rotational component is the mean between the vectors OC, OC_1 and OC_2 and is obtained by drawing a line from O to the centroid of the triangle $O\ C_1\ C_2$ that is $O3$. By describing a circle with radius $O3$ and center O, and taking points *1* and *2* respectively 120 deg. and 240 deg. lagging behind 3, the complete symmetrical negative phase rotational component 1, 2, and 3 is obtained.

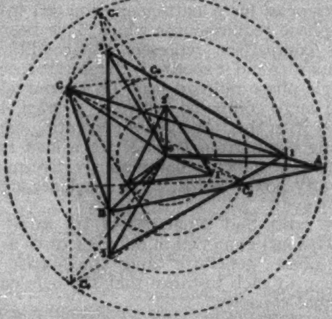

FIG. 10.—UNBALANCED THREE-PHASE SYSTEM RESOLVED GRAPHICALLY INTO TWO BALANCED SYSTEMS OF POSITIVE AND NEGATIVE PHASE ROTATION.

The positive phase rotational component is obtained in a similar manner, $O\ C_3$ and $O\ C_4$ having their vectors corresponding to $O\ C$ in symmetrical positive phase rotational systems based on OA and OB respectively. The vector $O3'$ of the positive phase rotational system corresponding to $O3'$ in the negative phase rotational system is the mean of the vector OC, OC_3 and OC_4 and is obtained by drawing a line from O to $O3'$, where $O3'$ is the centroid of the triangle $C\ C_3\ C_4$. The triangle representing the symmetrical positive phase rotational component is obtained by drawing the circle 1 2 3 with O as center and $O3'$ as radius, the points 1 and 2 being taken respectively 120 deg. and 240 deg. in advance of 3.

DISCUSSION ON "SINGLE-PHASE POWER PRODUCTION" (ALEXANDERSON AND HILL), SINGLE-PHASE POWER SERVICE FROM CENTRAL STATIONS (GILMAN AND FORTESCUE), PHILADELPHIA, PA., OCTOBER 13, 1916.

R. E. Doherty: I have some facts regarding the relative cost and efficiency of the different types of machines, which may be helpful in crystallizing ideas regarding what may be the most practical machine for this purpose.

The relative merits of different kinds of machines for the generation of single-phase power have been discussed in the several papers in terms of expediency and, in a general way, of cost and economy. A decision on what is the most practicable means of generating this power can be brought within more definite lines by supplementing that discussion with a comparison of relative costs and efficiencies for a particular proposed installation.

The single-phase requirements which have been chosen as a basis for this comparison represent the conditions for which operating companies find it necessary to resort to special apparatus, namely, a single-phase railroad load, or its equivalent, in which the peaks are large compared with the average load and also large compared with the three-phase generating capacity.

The following comparison is made for a load requirement of 5000 kw., unity power factor, continuously; five-minute peaks of 12,000 kw., unity power factor. The machines are compared in two different ways:

1. Relative costs and capacities of the same frame (same magnetic dimensions) equipped in different cases as a phase converter, single-phase generator and three-phase synchronous motor, assuming in each instance that the overload will be 2.4 times the normal capacity.

This is shown in Table I.

2. Relative costs and losses of a phase-converter set, a motor-generator set, and a steam-turbo single-phase generator. In each case the set is to meet the above specifications of 5000 kw., continuously, and 12,000 kw., five minutes. This comparison is shown in Table II.

TABLE I.

	Capacity	Cost
Three-phase synchronous motor..................	100	100
Phase converter (series or shunt)................	90	115
Single-phase generator..........................	66	100

TABLE II.

	Losses	Cost
Shunt-phase-converter set......................	100	100
Series phase converter (without transformers).....	85	65
3-phase motor, 1-phase generator................	186	118
1-phase turbo-generator.........................	123	96

In Table II the exciter capacity for all machines is included in the cost; and in case of the phase converter one additional voltage regulator is included.

As regards the factors of efficiency and cost, therefore, the figures in Table II are very much in favor of the phase converter, as compared with a motor-generator set. A complete comparison with a single-phase generator, including the losses and costs of the apparatus which supplies the motor-generator or the phase converter, depends of course upon local conditions. But the figures in Table II give a basis for such a comparison.

Where load is taken off different phases, the shunt phase-converter set, of course, must be used. If the load is taken from one phase only, and the power factor is not low enough to seriously affect the voltage regulation, the series converter seems to be the more promising.

The regulation of a series converter for the normal and overload capacities as assumed in the above comparison would be about 1½ per cent for full load, 5½ per cent for 2.4 times full load.

If it becomes general practise to correct the power factor of the single-phase load from an outside source, as indicated in Mr. Eglin's paper, the usefulness of the series converter will be greatly enlarged.

H. G. Reist: The problem of obtaining single-phase current of large quantity, has been with us for a long time. It has not been found entirely satisfactory to take varying single-phase loads from three-phase generators or from single-phase generators.

If single-phase current is taken, for instance, from a three-phase system, it unbalances that system. The unbalancing cannot be prevented by compensating windings on the pole pieces. If it is a fluctuating single-phase load, it will cause fluctuations in the polyphase circuits, and will interfere with any lights that might be on the system. It also interferes with motors in causing them to operate less efficiently and at a lower output. In general, it is not satisfactory, provided the power is sold, although in some cases it might be tolerated if the maker of the power used it himself. It would seem then, that heretofore, the only way of satisfactorily obtaining single-phase power was from single-phase generators. This, when it is produced by a power company, involves a separate system not tied in with the regular power producing apparatus. With a pulsating load, such as has been discussed, it means that the generating set is only lightly loaded much of the time and, therefore, must be very wasteful.

Most of the power now is obtained from steam turbines, and the generator problem is quite a serious one in these units, especially as we get to larger sizes.

It is well known that a single-phase generator has to be about 50 per cent larger than the corresponding three-phase generator for the same power factor; that the power factor required from single-phase generators is usually about 70 per cent, being much lower than is demanded from three-phase generators; and that the necessary addition of a squirrel-cage winding requires the turbine generator field structure to be about double the size necessary for a standard three-phase generator.

In a turbine generator the largest losses are usually due to windage, and these are very greatly increased by enlarging the field over what will be necessary for generating three-phase current.

However, as I said before, probably the increased losses from this point are less important than the great losses in the steam turbine, due to running much of the time greatly under-loaded.

Mr. H. L. Wallau: So far the problem has been attacked from the point of view of the relative advantage of a single-phase load on the generating station.

As our industrial developments have grown, however, and we now get fairly large furnaces and welding machines, we are going to have to meet the problem of supplying these single-phase loads on substations of relatively small capacities, compared with the generating station.

In such cases the single-phase generator would not be an applicable solution, as it would necessitate carrying the supply lines back to the generating station, or installing an expensive motor-generator set. It would seem, therefore, that the phase converter would meet this problem best, when it became sufficiently serious to require remedying.

Mr. Alexanderson, I think, has pointed out that whenever we can get the customers to buy the phase converter, the series machine is the one to recommend: but when the power company has to buy the machine, the shunt converter should be purchased.

Mr. Eglin also brought up the point today that every customer should have his power factor corrected by condensers so as to give a unity power-factor load.

Recently one of the manufacturing companies has developed a new type of condenser which can be made relatively small, immersed in an ordinary transformer case and sealed with oil, and I think it might not be difficult in certain cases, at least where there was an inducement in the rate, to have the customer put in enough capacity in this type of condenser to materially improve his power factor, if not to bring it up to unity.

Balanced three-phase unity power-factor load is most economical for generation and distribution. It follows that the most logical place to put in corrective apparatus for either power factor or unbalanced load correction is at the point or points where the load differs from the ideal load, and if the correction can not be made at this point, it should be made as near this location as possible, rather than at the generating station. The phase-balancer and synchronous condenser best lend themselves to such an application.

H. R. Summerhayes: In stating that a phase converter was less expensive than a motor generator in larger sizes, and it might be of the same cost in smaller sizes, I did not mean to indicate that the motor generator should be preferred.

I thoroughly agree with Mr. Eglin that the motor generator should be in the discard, except for small applications, and where the load is taken off of one phase. Even in this case it may be possible to use, what Mr. Alexanderson calls the series converter, at less cost and lower losses.

Mr. Torchio said that he had stated clearly in his paper the reason why it was decided not to tie in the single-phase railway system and its generating system, with the 25-cycle polyphase generating system of the New York Edison.

I can appreciate that the problem of division of loads is a serious one, but I merely wish to point out that it might be an engineering possibility to put in a balancer; and I believe that the division of load could be taken care of by the adjustments of the governors; certainly they would have to put in a voltage regulator, as Mr. Torchio states, but even if the peak loads were taken in a larger proportion by the larger station, provided it was taken care of by voltage regulators, it would not appear to be a very serious matter.

Here in Philadelphia they are operating now with peak loads of some 20,000 kv-a. single-phase on a system of less than 50,000 kw.

That is to say, they were running this afternoon two generators, totaling less than 50,000 kilowatts.

There were peak loads of nearly 20,000 kw. single-phase coming on, and the voltage regulation was good, so that it would appear possible on a larger system to do the same.

In the matter of synchronous condensers Prof. Scott and others were inclined to recommend making the generators larger, making them capable of taking care of the poor power factors.

Personally I am a strong advocate of the synchronous condenser. I do not think that the central station people, all of them, have given the matter sufficiently close study. I know it has been studied a great deal, but I do not believe that it is fully realized that the line losses at 70 per cent power factor are double the losses at a 100 per cent, and at 60 per cent they are three times. Very frequently it can be worked out that the saving in line losses alone will justify the installation of a synchronous condenser.

The investment in cable should be taken into account, and the investment in the cost of the generator.

A synchronous condenser, it must be remembered, is the cheapest kind of synchronous machinery; that is, it can be made at a selected speed, so as to have the lowest cost per kilowatt. Furthermore, it can be made to operate without attendance.

I do not see, because a piece of apparatus rotates, why it should require an attendant any more than a transformer does.

Automatic apparatus for converters and condensers is now coming into use, and I believe will be more widely used.

EXPLANATION OF THE ACTION OF THE PHASE CONVERTER

In order to balance the single-phase load and distribute it equally on the three phases of the generator, the three currents of the generator must be made equal and each current will be 1 divided by 1.73 or 58 per cent of the single-phase load current. Designating the single-phase load currents as *A* and *B* (see Fig. 1) the current *A* is composed of two components. A_1 coming from the generator equal to 58 per cent of *A* and 30 deg. out of phase with *A*, is the known component. By graphical solution (see Fig. 1) the other component of current *A*, which we will designate as A_2, coming from the phase converter is equal to A_1, 30 degrees out of phase with *A* and 60 degrees out of phase with A_1 In other words, *A* is composed of two components combined at 60 degrees phase angle.

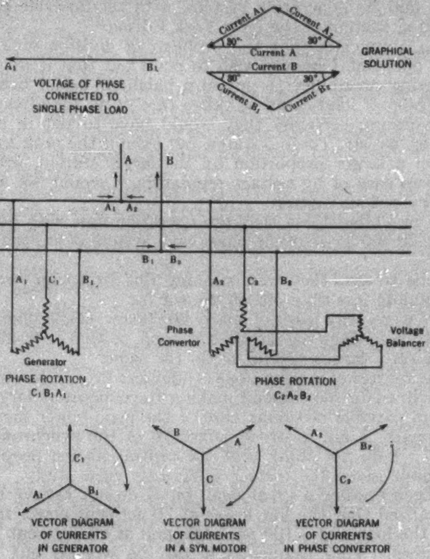
Current A₁
Current A₂
30°
30°
Current A
Current B
30°
30°
Current B₁
Current B₂
GRAPHICAL SOLUTION
A₁
B₁
VOLTAGE OF PHASE CONNECTED TO SINGLE PHASE LOAD
A
B
A₁
A₂
B₁
B₂
A₁
C₁
B₁
A₂
C₂
B₂
Generator
PHASE ROTATION C₁ B₁ A₁
Phase Convertor
Voltage Balancer
PHASE ROTATION C₂ A₂ B₂
C₁
A₁
B₁
B
A
C
A₂
B₂
C₂
VECTOR DIAGRAM OF CURRENTS IN GENERATOR
VECTOR DIAGRAM OF CURRENTS IN A SYN. MOTOR
VECTOR DIAGRAM OF CURRENTS IN PHASE CONVERTOR

FIG. 1—CURRENT RELATIONS IN PHASE CONVERTER

On the other leg of the single-phase load we will designate the current as *B*. At any given moment when *A* is the outgoing current, *B* is the incoming current. *B* is equal to *A* and they are 180 degrees apart. In a manner similar to the above we find that

B is composed of two components each 58 per cent of B and 30 degrees from B in phase relation, B_1 coming from the generator being 60 degrees from B_2 which comes from the phase converter.

Completing the vector diagram of currents on the generator since the currents are balanced and 120 degrees apart, we find that the third phase of generator current is C_1, as shown in Fig. 1. This same current C_1 flows into the phase converter, but since the generator current is an outgoing current and in phase with the voltage (at 100 per cent power factor) and the current C_2 flowing into the phase converter is a synchronous-motor current, C_2 when represented on a vector diagram will be 180 degrees from C_1 and at 100 per cent power factor would be 180 degrees from the bus voltage like any other synchronous-motor current.

By combining the three vector currents, A_2, B_2 and C_2 we obtain the vector diagram of currents in the phase converter and find that these currents in order to balance a given single-phase load are equal to the currents in the generator. The current C_2, like any synchronous motor current is 180 degrees out of phase with the generator current, but the currents A_2 and B_2 are only 60 degrees out of phase with A_1 and B_1 and on the vector diagram it is seen that the phase rotation is in opposite direction to that of the generator, whereas in the vector diagram for a synchronous motor the currents are all 180 deg. out of phase with the generator currents and the phase rotation is the same as for the generator. In the phase converter the voltage of the large machine is in the same phase rotation as the generator voltage but on account of the voltage distortion produced by the voltage balancer the currents in the phase converter are in opposite phase rotation to those in the generator.

The unbalancing of currents in the generator produced by single-phase load is accompanied by a distortion of the voltage triangle and in order to bring the currents in the generator back into balance we must produce internal voltages in the windings of the phase converters of such magnitude and phase relations as will produce the currents necessary to combine with the balanced generator currents to supply the single-phase load currents. Since the currents in the phase converter to accomplish this balancing must be in opposite phase rotation to those in the generator, while the main counter e.m.f. produced in the phase converter is in phase with the generator voltage, the currents in opposite phase rotation to the generator currents are produced by introducing in the Y connection of the phase converter a smaller three-phase machine mounted on the same shaft and driven by the phase converter. This machine is designated as the voltage balancer and is so connected as to have opposite phase rotation to the phase converter.

The revolving field of this machine is not a definite pole construction but consists of a laminated structure containing slots in which there are two field windings at right angles to each other in space (see Fig. 2).

By exciting field winding 1 in a positive direction a three-phase current is generated of opposite phase rotation to that in the converter, but in a certain phase relation to it depending on the relative positions of the stators.

The stator of the voltage balancer is mounted in a cradle so that it can be fixed in different angular positions with respect to the position of the stator of the phase converter.

By exciting the field 2 only, three-phase currents will be produced with a phase relation of 90 deg. to those produced by field 1 only. Fields 1 and 2 may be reversed thus producing phase relations 180 deg. from the two former positions and by exciting 1 and 2 at the same time and to the same magnitude the intermediate forty-five degree positions are produced. By exciting 1 and 2 at the same time, but with different magnitudes, the voltage of the balancer may be made to assume any desired phase relation with respect to that of the converter.

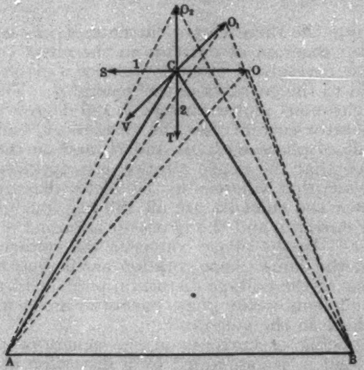

Fig. 2—Voltage Relations in Voltage Balancer and Phase Converter

Referring to Fig. 2 the delta *A*, *B*, *C* represents balanced voltage on the generator.

When single-phase load is taken off the phase *AB* the voltage triangle will be distorted. If the single-phase load is of 100 per cent power factor the point *C* moves in the direction of *CO* and the voltage triangle becomes *AOB*. If the load is at 70 per cent power factor (45 deg. lag.) the point *C* moves in the direction of CO_1 and the voltage triangle becomes AO_1B. If the single-phase load were of zero power factor point *C* would move in the direction of CO_2 and the voltage triangle becomes AO_2B.

By properly combining the direction and magnitude of the fields in the voltage balancer we can produce a voltage distortion opposite to that produced by the single-phase load and this will cause currents to flow which will balance the single-phase load in the generator. It is possible, for instance, to set field 1 so that when used alone it will produce a voltage distortion CS opposite in direction to CO and field 2 so that when used alone it would produce a voltage distortion CT opposite in direction to CO_2, the combination of these two fields would obviously produce a voltage distortion CV opposite to CO_1. Thus field 1 would compensate for single-phase load at 100 per cent power factor and bring the voltage triangle back to normal, field 2 would compensate for single-phase load at zero power factor and a combination of the two fields in equal magnitude would compensate for single-phase load at 70 deg. power factor or 45 deg. lag when this load is applied on phase AB. For any other power factor the two fields could be used in different proportions.

It is assumed in the above case that the voltage of the phase AB is controlled and held constant by the generator regulator, so that, the single-phase load does not affect the voltage AB.

It will be noted that when unity power-factor single-phase load is thrown on and the voltage triangle tends to assume the shape AOB, that the voltage AC is increased and the voltage BC is decreased. For lower power factors both voltages may be increased. Therefore, if a voltage regulator is connected across phase AC and made to regulate field 1 and another regulator is connected across phase BC and made to regulate field 2, these regulators will so control the fields as to maintain the voltages AC and BC constant and in so doing currents of the proper phase relation and magnitude to balance the single-phase load are produced in the windings of the phase converter, these currents being made to flow by the internal voltages generated in the voltage balancer, which overcomes the impedance in the windings of the phase converter.

When the single-phase load is thrown on phases AC or BC the voltage triangle is again distorted, point C moving in a different direction but regulators which are arranged to reverse the fields when necessary will so control the fields as to deliver the proper balancing currents no matter what direction the point C tends to move.

In the main machine or phase converter an action goes on in the squirrel-cage winding which may be explained as storage of power from the phase C and delivery to the phases A and B.

In actual practise the currents flowing to the converter will be slightly unbalanced on account of the losses in the machine, but the generator currents will be balanced.

R. E. Gilman: It is the single-phase load, superimposed on a polyphase system which causes voltage unbalance.

It must remembered that all the machines on the system are in parallel and consequently the voltage unbalance is common to all. This distortion is due to unequal impedance drops in the various phases of any machine. These drops are necessarily the same in corresponding phases of all machines. That is the phase and magnitude are equal for corresponding phases. The currents therefore are inversely in proportion to the impedance of the machine. To force any machine to assume all the unbalanced load, all that is necessary is to reduce the equivalent impedance of that machine to zero. This can be done by introducing one or more voltages of the proper phase and magnitude to neutralize the inherent impedance drop of the machine.

The shunt phase balance as described is a particular solution of the problem based on introducing a voltage in series with each phase of the machine which is to assume the unbalanced load. These boosting voltages are all equal and make up a polyphase system with opposite phase rotation to that of the main unit.

W. C. L. Eglin: At a Chicago meeting some years ago Dr. Steinmetz presented a paper on "The Reliability of Power Company Service" and pointed out very clearly that the standard for reliability of service was the simple d-c. distribution, and that with the increasing general use of alternating current we had to go back to the simple standards laid down by Mr. Edison for satisfactory general power distribution.

He also pointed out very clearly that if the proper study of the power companies' requirements, and the consumers' requirements was made, there was no reason why a-c. systems could not follow along the lines laid down by Mr. Edison and be equally as reliable. The particular feature emphasized was the proper use of reactances.

As has been brought out by Mr. Gilman, the main difficulties are in producing a satisfactory phase converter or phase balancer. All that he says is true, and all of these difficulties have been overcome by Mr. Alexanderson and his assistants.

Whatever phase the unbalance comes on, it is automatically taken care of. The dangers of a heavy short circuit have been taken care of in the two ways; first, by the limiting of the reactances on the feeders; and second, by the limitations put on the regulators; so that there is a limiting load which can come on the phase balancer.

In this work there is one other feature to be considered and that is the correction for power factor. As has been pointed out, very serious losses are involved in the transmission system with a low power factor.

With large loads it is essential in my judgment that they must only be considered on the basis of unity power factor. All of the problems then, including the balancing problem are infinitely easier. The corrections for power factor should be part of the equipment.

I think Mr. Reist has very clearly shown that in the large size generators the complications in building are bad enough now without adding to the size, to take care of something that can be taken care of in a different way.

I was asked to state something on what it costs to produce single-phase power.

It is very difficult to answer that exactly. We determined first that we would work for the power house to be the most economical that could be built. That necessitated that we fix some standard of power factor. From our studies of the results of correcting poor power factors, we were convinced that we should put in sufficient synchronous apparatus to obtain unity power factor.

In a power station the load is not fixed, it is constantly growing from year to year, and an inductive load added varies with the different character of customer's loads, so that you cannot say that your power factor will be 80, 90 or 95; it may be that one year, and greater or less the next year.

That made us desire at first that the generator be designed for unity power factor, and that it have no dampers for the reason that dampers add, as has been explained, first to the size of the machine, and secondly to its first cost. We would take care of the unbalancing of load in some other way.

All of the methods that were described here were carefully discussed and analyzed, as far as our conditions were concerned, and we determined on the phase balancer. Naturally there were skeptics, some fears as to what we could accomplish, especially as we were depending largely on automatic devices to overcome some of the difficulties.

A number of people have seen this machine in operation, and it has fulfilled every condition that has been expected of it; in fact, I think it works a little better than most of us expected.

I was asked also what was the biggest single-phase load that we would have to carry.

The principal single-phase load, in fact the entire single-phase load that we have today, is for electric railroad operation.

We endeavored naturally to have the various sections of this single-phase load distributed over the three phases of our bus bars, and our contracts provide for the sale of three-phase power. That is very difficult, especially in the starting of a system; The railroad starts with one division which can be put on one phase, another division may be put on the second phase, and a third division may be put on the third phase; so that we get a certain amount of fixed balance under these conditions.

The operation of a railroad, however, or any other load, even 5000-kw. electric furnaces, is not continuous; it may be shut down. You may have three 5000-kw. furnaces, and if one is shut down, you have a condition of unbalance, so that the phase balancer size has to be the size of the largest single-phase load that you may have to supply. That, in this case is the heaviest division of the railroad, to which we have supplied I think about 30,000 kv-a. The phase balancer, of course, as has been pointed out before, does not have to carry all of that unbalanced load because of the other synchronous apparatus that is on the bus-bar system, all of which tends to balance the load.

This load is corrected for very nearly unity power factor, and the synchronous condensers are installed in a sub-station about midway of the electrification, so as to get the real advantage of the correction of the power factor, reducing the line losses and maintaining the uniform voltage on the lines. The synchronous condenser in this case has a double purpose.

There is another point that has come up, and that is a question of frequency. There have never been any real standards of frequency established. I do not think any two standards can ever be called a standard. We have had the so-called 25-cycle and 60-cycle systems. I should very much like to see the Institute, through its Standards Committee, take up and solve for the industry at large, the question of the American standard frequency; and I think that will do more to help the development in every way, both in the use and sale of power and apparatus, than probably anything else that the Institute can do.

B. A. Behrend: Mr. Eglin suggested the standardization of frequency. Now, let us understand the fundamental reasons which underlie the difficulties in the generation of single-phase current. They are due to the turbo-generator which has completely superseded the multipolar reciprocating generating units of ten or fifteen years ago.

It is very easy to design an electric generator of say 25,000-kw. capacity or even 50,000-kw. capacity, provided it is a multipolar unit, as a single-phase generating unit.

It is not possible at the present state of the art to make a single-phase generating unit for a capacity in excess of say 15,000-kw. and I should prefer to limit the capacity of the single-phase unit to 15,000 kv-a. considering the nature of the load, which of course is a railway load of a low power factor.

C. A. Adams: How many poles?

B. A. Behrend: I refer to two-pole units. Now then, where does the question of frequency enter into our problem? It is at the present state of the art not possible to design single-phase motors, and therefore locomotives, for 60-cycles, which frequency Mr. Eglin doubtless had in mind, when he made his suggestion for the standardization of the frequency. In this world unfortunately conditions are not as we want them to be, and we have to recognize the facts as they are.

Two-pole single-phase generators are difficult machines to design, as Mr. Reist has pointed out, and as is so well known to us.

Mr. Eglin has stated that it is necessary in modern power plants to use a certain amount of reactance in the generators and feeders, and it may be added that the increase of the internal reactance of the generators has increased the difficulty of designing the damping circuits on the revolving elements of the turbo-generators, as the dampers have to be in proportion to the strength of the armature. Turbo-rotors travel at a circumferential speed of approximately four miles a minute; at which speed the centrifugal forces developed are terrific. The conducting materials at the present state of the art have no considerable mechanical strength. In a device which we have developed they have to be hammered and peened into the chrome nickel steel end rings in a somewhat complicated manner, in order to hold them in place, and prevent them from shifting and bending.

There is also great difficulty in obtaining and securing satisfactory contact between the axial copper conductors and the circumferential conductors.

Therefore, it may be stated that the capacity of single-phase generators is limited; and the engineers who have an opportunity to specify the unit capacity of such generators should be very careful indeed not to demand of the manufacturer too large a unit as it involves frequent repairs, and imperils reliability of service.

This is the fundamental reason for the question that has been considered in the sessions today, Mr. Alexanderson having given us a means of utilizing the existing 25-cycle three-phase power plants for the generation of the single-phase currents, so far as this 25-cycle single-phase current is going to be used in the operation of our great railway systems.

Now then, in the case of 60-cycle power plants, we are confronted with an additional difficulty, viz., the difficulty of transforming from 60 to 25 cycles; which must be done by motor-generator sets. Therefore, in this case Mr. Alexanderson's invention can be dispensed with.

The question of power factor is one of great importance, and I agree with Mr. Eglin that it is desirable that every one of us should give it a little more attention; but by giving it a little more attention we do not raise the power factor.

The peculiar conditions of railway operation, the peculiar nature of the single-phase railway system, combine to make the power-factor problem a very formidable one, with a low load factor, if a power plant is devoted exclusively to the generation of single-phase electric currents.

These are difficulties which a year or so ago made me remark, that, when Mr. Wynne discussed the electrification of the Norfolk & Western railway system, it was the "least unsatisfactory solution" of an intensely difficult problem for which remark my friend, Prof. Scott, took me to task and was very hard on me. I am afraid, however, my statement must stand, since, unless we realize that we are solving these problems temporarily in the least unsatisfactory manner, solutions good enough to hold their own but no better, we shall not advance.

D. W. Roper: I disagree with Messrs. Gilman and Fortescue, as to the latter part of their conclusions, which favors steam-driven single-phase generators.

To take the case in Philadelphia, for example, where they have a load of say 25,000 kv-a., and with the figures given by the previous speaker, it would require at least two single-phase generators to carry that load.

The exigencies of central station operation require that some reserve should be kept for the generating apparatus, and that would mean the installation of three machines, any two of which may carry the load.

I think central station men will also agree that idle generating capacity on the peak of the load is undesirable.

It would therefore appear that if the short-circuit conditions are of any serious moment in determining the design of your plant, that those conditions should be met by reactors, or other similar protective devices, rather than by any scheme which contemplates idle generating capacity on the peak of the load.

G. H. Hill: The first generated current ever produced was a single-phase current, and it seems curious that at this time there is need of such a considerable amount of discussion, to make clear how that first single-phase current can best be produced for use commercially. I would like to emphasize the fact that this problem is a general one. We cannot confine ourselves to particular applications.

Mr. Torchio's solution none of us will criticise, because he has met his conditions in the way that fits the situations best; he has by inheritance a complex system, 25-cycle and 60-cycle, three-phase and single-phase, all of which had to be taken care of, but I feel sure that he would not duplicate his entire system if he had it to do over today. I think we must keep in mind the ideal in discussing this problem and make sure that we establish a reliable guide for industrial development.

I belive there is not much doubt in the minds of those who are acquainted with the situation over the whole country that the question of cycles is answering itself.

In the East where the power plants are oldest, we have numerous excellent 25-cycle systems, but in the West, which is the stronghold of transmission and water-power developments, 60 cycles is almost universal and you cannot convince our western friends that there can be anything but 60 cycles as the standard frequency. From the experience along this line an illustration may be drawn of the fallacy of trying to make compromises.

The old question as to what frequency should be used generally led a number of engineers to the opinion that a compromise on 40 cycles would be about right but no attempt was made to establish 40-cycle apparatus as standard. Failure to do so was inevitable because the compromise was not the best frequency for either lighting or power. The net result is a local section handicapped with a frequency that requires special apparatus.

The same idea applies to a large extent to the question we have here. Single-phase power is perfectly easy, in an engineering sense, to produce in a number of ways.

It can be a separate system, single-phase generators and transmission system independent of the other power system; but this does not meet the ideal conditions at all. We cannot advocate such duplication and separation of power loads as a solution of anything except perhaps some local situation.

You can produce single-phase power from polyphase generators by adapting these generators so that they will deliver an unbalanced load without overheating, and without seriously affecting the value of the polyphase power, but the result is a compromise which is not a solution because it will not be acceptable as best for either polyphase or single phase.

The effect of unbalancing a polyphase system is bound to be bad in one way or another and even if you attempt to balance the single-phase loads among the phases as pointed out by a number of speakers, the asynchronous application of these loads is bound to occur and there must be a regulating device to correct the resulting unbalancing. Such an arrangement is a poor compromise because it handicaps the polyphase in first cost and complication, and restricts the use and convenience of the single phase. It would be a handicap in the development of the art because you could not be free to choose the most economical system. It does not lend itself to either old systems or extensions of systems in a way that we ought to set down as an ideal.

What we want is a means for producing single phase, retaining the standard and best form of generator and transmission, without duplication, without segregation of load, without raising the cost and without affecting the value of the polyphase system for any purpose for which it is useful. Such a means is now suggested and the conclusion seems inevitable that it is the ideal, and one toward which we should look for the solution of the problem.

If there is involved a change in frequency it is necessary to use a motor generator. If the motor-generator sets are not perfect (as one speaker implies) they are certainly very practical and very successful and we do not know of any other way to change frequency than by two rotors, that is, in a commercial way for power purposes. I know no reason why motor generators should not be used to produce single-phase current of a low frequency from a polyphase system of a higher frequency.

While single-phase railways demand low frequency there will be a considerable amount of use of single-phase current of 60 cycles, for furnace work and heating work, especially in the West. For this, 60 cycles is absolutely satisfactory and a phase converter will supply the single-phase demand from a 60-cycle three-phase system, without unbalancing or affecting it adversely in any way.

Moreover it is particularly fortunate that we are able to take a single-phase load from a three-phase system in the way particularly suited to the character of the single-phase load.

If it is possible to approximately balance the single-phase load on the three-phase system and most convenient to use the transmission system as a bus line, then the shunt converter can be used to correct the unbalancing in the loads, so that the three-phase supply is not affected.

The series converter is particularly adapted to take three-phase power as an absolutely balanced load and supply a large single-phase load, where it is sufficiently great to warrant a special substation.

I cannot sympathize very much with the point of view that has been brought out, that there are a great many complicated reactions in this converter. I know that every polyphase circuit is awfully busy. If we try to follow out all the reactions, phase displacements and frequency distortions that are going on, the matter is very complex.

But I know that the converter accomplishes all these things, does keep in phase, does give the regulation desired, does draw balanced polyphase load, and does deliver single-phase load of good regulation. This has been pretty well demonstrated and I think that the manufacturing companies will be prepared to supply such apparatus under proper guarantees of successful operation to those that require it.

The phase converter is practical, flexible and efficient, and considering the needs of the whole system and the future development, I cannot see why it should not be accepted as the ideal solution of the problem.

Philip Torchio: I am very glad to hear of the completely successful operation of these balancers in the Philadelphia station. Personally I feel very much gratified that we can dispose of such apparatus in our requirements.

In discussing this matter, Mr. Hill has just now emphasized to some extent that there are two problems to take care of; one is the 60-cycle distribution and one is the 25-cycle railway load. They are entirely different services.

The single-phase loads from a 60-cycle system, used for welding machines, furnaces and services of that character, if they cannot absolutely be balanced among themselves, will necessarily require some balancer, such as Mr. Alexanderson has developed because the upsetting of the voltage balancing on the distribution system would be too severe to be tolerable.

I have no hesitation in advocating such a piece of apparatus in a 60-cycle system which must carry unbalanced single-phase loads. The arrangement is ideal. There is no question about that; I do not want to be understood that I take any exception to it.

My point is that, whenever a company operating a 25-cycle system has to supply single-phase railway loads, such company should for new equipment install generators having the single-phase characteristics. In our special New York conditions we had an additional object in selecting the plan described in my paper—that was to be able to operate in parallel with the other station of the railroad company, because, by running all the railroad system in parallel, we secured that very object which Mr. Eglin emphasized in his paper as derived by the diversity factor of the peak loads of an amplified system, evening up the resultant combined load. Railway loads are just of the character to require combining, and our perfect parallel operation and sharing of peaks with our customer's station has undoubtedly contributed to the satisfactory result of our service to the New Haven Company.

Coming to the economic features of our solution, involving generators with single-phase characteristics compared with an installation with balancers, if Mr. Doherty means that we are running at 123 per cent loss, compared with 85 with the balancers, I take issue with such a statement. I would only state that it is not a fact. It is very far from the fact.

There cannot be 45 per cent greater loss in our system than with the balancer. I believe that our losses are not any greater, and I believe that they are less, that our efficiency is better. We have a turbine specially designed and equipped with an additional set of nozzles controlled by a hand operated valve to give high economy at low loads.

That machine, without the special valve, would operate at higher average loads with practically the same efficiency as a standard machine operating at its most economical point. But in our actual operation we have something in the order of a fraction of a pound of steam per kw-hr. more consumption than we would have, operating at the most economical point; but that is all the difference, and that could not account for the difference between 85 and 123.

As far as the extra cost of this special machine is concerned, in comparison with a balancer installation, I do not like to see the comparison between 65 and 96. I don't know what is compared there.

If it is meant to say that our cost is in the relation of 96 to 65, I will say that the actual figure of extra costs of the single-phase generators, as estimated by the manufacturers, were $16,000 a machine, or $32,000 total; that was all the extra cost we paid, and we have been doing a satisfactory business for ourselves, and giving entirely satisfactory service to the customer.

As I stated, we discussed the balancer at the time, but then the balancer was not developed and was not ready to use.

If Mr. Alexanderson's balancer proves, and, as I have said before, I am happy to hear that it has proved, satisfactory, all we have to do is to spend that money buying the balancer and then we are better off than we were before; we utilize in its entirety all of our equipment; we have not lost one cent in any other respect except that we have paid the $16,000 extra per machine, and in the meantime we have had two years' service before the development happened.

In concluding, I would say that even this trivial extra cost of installing machines with single-phase characteristic would not be a loss; I don't know what the 5000-kw. balancer costs; probably we would need a larger machine for our load; the cost of one balancer would certainly be in the order of the $32,000 that we paid extra for our generators; if we did not have the single-phase characteristic machines, we would have had to buy at least two balancers, one for spare, whereas now one would be sufficient, because if it breaks down, our generators would carry the single-phase load, as they do now.

The saving that we make of an extra balancer, I think, must at least balance the extra cost we paid for the generators, and so we come out even.

To come back to my original proposition—and I am not talking derogatory to the balancer system in any way—but I really believe that central stations distributing commercial loads should put in generators capable of taking care of poor power factors, and unbalanced or single-phase loads.

I think it is a wise investment; it makes better and more durable machines, it enables the station to do a lot of things on emergency, and I think it is not going to be very costly.

R. E. Doherty: The comparison of loss of 85, in the case of the series converter, against 123 in the case of the single-phase turbo-generator, was this:

The phase converter is capable of delivering 5000 kw. continuously and 12,000 kw. for five minutes.

A single-phase turbo-generator, to deliver the same load, would have losses of 123 instead of 85.

The figure 85 represents the losses of the series converter, the one machine by itself operating at 5000 kw., 123 represents the losses in the single-phase turbo-generator when it is delivering 5000-kw. single phase, a ratio of 123 to 85.

The difference between 85 and 100 represents the losses in the auxiliary machine, which is known as the voltage balancer.

H. G. Reist: To be fair, should you not include the general losses?

C. A. Adams: The three-phase generator losses in the machine that supplies the series converter?

H. G. Reist: Yes, exactly.

R. E. Doherty: These figures are not intended to be a comparison of the losses from the steam to the single-phase load. It is intended only to give the losses in a single-phase turbo-generator when it is delivering the same load as a series converter.

H. G. Reist: Yes, but the series converter first goes through the generator, and has separate losses.

R. E. Doherty: Yes, indeed.

W. C. L. Eglin: I think Mr. Torchio has brought out very clearly his presentation of what the great future for all of that work is, *i.e.* in the future extensions, the enormous growth of power-house apparatus. The dollar saved in the generators is in a constantly increasing amount, that is, it will not be necessary in the future to equip all the generators with dampers, etc.

It is not only the added cost of the increased size of the generator, but there is positively a reduction in the efficiency; that is, the machine is not as efficient as if it was made without dampers.

Peter Junkersfeld: I would like to add a comment on this matter of power factor. I am referring now, not to these few large systems that have single-phase railway loads, but to the very much greater number of central stations over the country. I want to make sure that the proper place for synchronous condensors is not misunderstood.

There are a great many systems over the country where the peak comes at night, when the lighting is almost the entire load, and when the power factor is of the order of 95 or 100 per cent. They may have a day load whose power factor is as low as 60 or 70 per cent, but the volt-ampere day load may be less than at night when the power factor is high; therefore in those cases the limiting feature of the size of copper in the distribution system is created by the night load and not by the day load. In such a case the synchronous condenser has not yet found its place, but the day load is growing at a very much greater ratio than the night load and it is only a question of time when these companies will find a place for the synchronous condenser.

C. F. Scott: One of my points was that the best place to provide for power factor and single-phase generation, is in the generator itself, being the simplest and often the cheapest way; that the applications to be made here are those that apply to the largest power plants where we are reaching the limits of size, and where the size of the auxiliary apparatus is itself very large, but that these considerations might not apply at all to smaller plants.

In the matter of synchronous condensers for correction, I think the point brought out by Mr. Summerhayes illustrates that it is not universally applicable. Specific cases must be considered carefully.

H. C. Albright: I understood Mr. Torchio to say that with his three-phase generators especially built for single-phase loads, carrying heavy loads, the voltages varied as much as 12,200, 11,000 and 13,900 on the various phases.

I would like to ask him whether this voltage distortion is not a serious handicap, and an objection for generation in that manner, over the phase balancers?

Philip Torchio: If I understand the question, it applies to the joint system of the New Haven and our system: They are operated on single phase purely, and will not affect any other customers at the present time, and therefore the question of a balancer, I could not answer.

E. F. W. Alexanderson: I do not know whether I can answer that question. Of course it belongs to the New Haven system.

Philip Torchio: The question of balancing; if the balancer was used, there would not be any unbalanced voltage.

E. F. W. Alexanderson: Yes.

Philip Torchio: The answer is there.

E. F. W. Alexanderson: Mr. Fortescue and Mr. Gilman, in their paper, brought out some very appropriate questions in regard to the possibility of short circuits, etc.

Those problems were real problems. Since Mr. Eglin has expressed his satisfaction in the way those problems have been solved, we have already the answer to them.

C. L. Fortescue: The questions raised in connection with the regulation of the phase balancer are real problems that have to be met in the phase balancer. They are not raised for the sake of controversy.

I think there is a big future for the phase converter, but I also think that in certain cases heavy single-phase loads can be better handled separately, than from a polyphase system, especially when the load is very large, and particularly if in order to handle the load the power company has to purchase new material.

I think that the statement, that a single-phase machine is not so good a machine as a polyphase because it has dampers, is not correct.

I think that the correct statement is, that a single-phase machine is a superior type of polyphase machine because it has dampers.

The dampers in the machine enable it to carry quite a considerable amount of unbalanced load without undue heating while with a balanced load they have no effect on the efficiency of the machine. The small amount of loss in space due to the damper, I think is very well met by the improvement due to its ability to handle unbalanced loads.

Philip Torchio: When the machine is running three-phase balanced, is the efficiency of the unit lower than a machine without dampers?

C. L. Fortescue: When operating as a balanced polyphase machine at the same load as the same machine without dampers, the effciency of both would be the same. The dampers are inert under this condition.

Philip Torchio: How much?

C. L. Fortescue: Mr. Eglin says that the balancer is assisted in handling unbalanced loads by the synchronous machinery on a system.

When the balancer is operating this is not true, except in so far as synchronous machinery improves the power factor of the unbalanced load; otherwise, the only way in which the synchronous machinery on the system can help to balance the single-phase load is by the actual distortion produced thereby.

In other words, the distortion is inversely proportional to the admittance of the system to the balancing or counterphase rotational current in the circuit.

C. A. Adams: Insofar as the balancer can not perfectly balance, other apparatus would assist?

C. L. Fortescue: Of course, if the balancer is not doing its work perfectly, the rest of the apparatus will help it out.

I think a great number of the comments made by the various speakers on single-phase machines have been due to considering particular cases.

If consideration is given to the fact that large railway electrifications demand large amounts of single-phase power, it begins to be evident that the relative amount of single-phase power as compared with polyphase may be so large, that new apparatus is required and therefore it seems to me that careful consideration should be given to the merits of separate single-phase generation.

If the peak loads of the single-phase system do not occur at the same time as the peak loads on the polyphase system, it is possible to combine the two systems, so that, the single-phase generators can be used as polyphase generators at the time of the high demand on the polyphase system.

Without reflecting on the balancer phase converter, I wish to bring out the principal point that should be considered in its development.

If the load is constantly changing from one phase to the other, which is quite liable to occur—for example if two single-phase railway loads are being supplied, the load is variable and high sudden peaks occur—the peak on one phase may occur at an instant when the other phase is changing suddenly from peak value to very little load. The changes in these peaks are very rapid, and the regulating part of the balancer has to take account of the peaks very quickly.

It can readily be seen that a condition may occur where a balancer is at the maximum regulating condition for the peak on one phase and at the same time as that load is suddenly lost, the load on the other phase comes on, in which case the balancer may produce a greater unbalance for the instant than if it was not there.

In other words, it is important to have the regulating apparatus very sensitive, and very quick acting.

As to the question of the operation of the present balancer, it must be remembered that it is operating to balance a single-phase load on one phase only.

The question is, how will it operate when it has to balance a variable single-phase load on two phases, such as will occur when the Chestnut Hill electrification goes into effect—will it be able to follow the sudden changes of load from one phase to the other? Is it possible to make a regulator sufficiently sensitive to give perfect satisfaction?

Mr. Behrend makes the statement that it is absolutely impossible to build a single-phase two-pole turbo-generator above a certain capacity. I think he must have meant, that at the present time there was no known way of building such a machine. I remember talking to a man who said that at one time a number of years ago he required a 100-kw. transformer, and submitted the problem to the engineers of two manufacturing companies. The engineer of one of the manufacturing companies said he believed it was absolutely impossible to build a transformer of such a size, the heating could not be dissipated and the reactance would be so high that it would be impossible to get good regulation, but the other manufacturer said he would be willing to try it out, but the purchaser would have to assume the risk. The purchaser was a good enough sportsman to take the risk and the transformer was built. Now we are building 10,000-kw. units, so that what it seems impossible to do today, may in a few years be quite practicable.

R. E. Gilman: In respect to the relative size and cost of turbo-generators, the limitation of the turbo-generator, especially the two-pole machine, is largely a question of field design. Take, for example, a 25,000-kw. 100-per cent power factor, single-phase generator, two-pole, it would be built on exactly the same frame as a 14,000-kv-a., 70-per cent power factor, single-phase machine; and if the same frame were used for a polyphase generator at 70-per cent power factor the approximate output would be 17,500 kv-a.

As to the relative cost and performance of the machine with or without dampers, the efficiency for the same machine operated as a polyphase machine, at the same power factor, is the same. The cost would be increased due to the damper, possibly 5 to 8 per cent.

In comparing cost of single-phase equipment against polyphase generators or phase balancers we must bear in mind that the single-phase turbo-generator is a part of the main generating equipment and that the shunt or series converter is an addition. These same remarks hold in comparing the efficiency of the two systems.

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THE EFFECT OF RECENT DECISIONS ON THE WORK OF INVENTORY AND APPRAISAL

BY PHILANDER BETTS

ABSTRACT OF PAPER

In order that our inventories and appraisals shall be useful in determining all of the appropriate elements of value, they must be classified as to age, condition, use, and extent of use in each class of service.

DURING the past few years there has been much discussion on the proper basis for rates. This discussion has been quite confusing at times because of the entrance into it of those who were not familiar with all sides of the question. That is, engineers not familiar with the existing legal decisions have argued pro and con on the subjects of valuation and depreciation, and lawyers not familiar with development cost have based their arguments entirely on the decisions of the Courts.

If we are to have proper respect for our Courts, we must abide by their decisions and, if not satisfied, we must familiarize ourselves with all of the conditions leading to the Courts' decisions. Probably the earliest cases which begin the history of decisions concerning valuation are those of the Brunswick and Waterville, Maine, cases. We must bear in mind, however, that those were cases in which negotiations were in progress looking to the sale by water companies of their properties to the municipalities. In those cases the franchise rights had either expired or the municipalities had the right to take over the properties as well as the franchises, and thereafter operate them. In "purchase and sale" cases, clearly the matter to be determined is the *value* of the property, all things considered, including "going concern" values if any exist. After a study of many of the great rate cases, the writer has come to the conclusion that the confusion of mind has come from the fact that the early decisions were based upon "purchase and sale" cases and did not primarily have anything to do with cost in its broad sense.

VALUE NOT COST

If we are, however, to do our work in conformity with the Courts' decisions, we must take as our primary basis for the consideration of rates, the value of the property and not necessarily the cost. Justice Harlan was wiser than he knew when, in the famous case of Smyth v. Ames, he said as follows:

> We hold, however, that the basis of all calculations as to the reasonableness of rates * * * * * must be the fair value of the property being used by it for the convenience of the public. And in order to ascertain that value, the original cost of construction, the amount expended in permanent improvements, the amount and market value of its bonds and stock, the present as compared with the original cost of construction, the probable earning capacity of the property under particular rates prescribed by statute and the sum required to meet operating expenses, are all matters for consideration and are to be given such weight as may be just and right in each case. We do not say there *may not be other matters* to be regarded in estimating the value of the property. What the company is entitled to ask is a fair return upon the value of that which it employs for the public convenience. On the other hand, what the public is entitled to demand is that no more be exacted from it * * * * * than the services rendered by it are reasonably worth."

REPRODUCTION VALUE v. ORIGINAL VALUE

The general trend of recent decisions has been to make reproduction cost the sole or controlling basis of value for rate purposes. Some Courts plainly state that, in their opinion, actual cost, capitalization and other factors are to be considered only to the extent that they may throw light on the cost of reproduction or existing depreciation. In support of this principle, the opinions of the Supreme Court of the United States, indicate that it is the "present value" of the property that is to be determined; thus, in Smyth v. Ames, reference is made to "the fair value of the property being used * * * * * for the convenience of the public"; in San Diego Land and Town Company v. National City, it is "present value"; in the same case, on appeal to the Supreme Court, Justice Harlan refers to "reasonable value of the property at the time it is being used for the public"; this is quoted as settled law by Justice Holmes in 1903, and by Justice Peckham in 1909 in Wilcox v. Consolidated Gas Company. It is argued that this constant use of the present tense by the Supreme Court in referring to fair value for rate purposes must at once exclude actual cost or original cost from having any controlling influence in the determination of fair value. Under this interpretation present value must be based either on market value or reproduction cost, and as market value is not usually considered a fair or possible standard for rate purposes, reproduction cost is turned to as the only available standard. This line of argument would be more convincing were it not for the fact that in the leading case of Smyth v. Ames in which the present value principle is laid down, it is also distinctly stated that both original cost and reproduction cost shall be considered in determining a fair present value, and it is no indication that either of these factors should be given a controlling influence. This cannot be accepted as the settled rule of law as the whole subject of valuation is still in a developmental stage. The Supreme Court of the United States has wisely refrained from laying down a hard and fast rule which might have to be reversed when all of the factors of the problem shall have been more clearly discussed.

VALUE NEW V. DEPRECIATED VALUE

In the so-called Idaho case, it has been determined by the Court that the value new of the property is the proper basis for computation of rates rather than a "present value" obtained by deducting the full estimated depreciation. This decision follows a number of commission decisions along the same general line and is best expressed in the words of the St. Louis Public Service Commission in the case of the Union Electric Light and Power Company of St. Louis, decided in 1911, "In depreciating, to arrive at the present value, the Commission does not consider it fair to make deductions for anything but the present physical condition and for items where it is plainly apparent that the property has become obsolete and inadequate."

PROPERTY USED AND USEFUL

From the earliest cases down to the present time, the Courts have been unanimous in the determination that the basis for rates must be the value of the "property used and useful" and have not been very definite in further defining these terms. The Commissions have, however, in a number of cases, after determining the value of the entire property, made deductions for property considerably in excess of that required for the present * customers or those who might be taken on in the near

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*San Diego Land & Town Co. v. National City.
Long Branch vs. Tintern Manor Water Co.
Mantua vs. New Jersey Gas Co.

future. This has sometimes occurred, and occurred recently in New Jersey, where companies have been too optimistic with regard to the development of the territory and have built plants far in excess of the actual needs. It also follows from this, that rates may not be based upon an inadequate plant but that the valuation to be determined will be that of a plant adequate in all respects for the customers now connected and including a reasonable reserve for customers who may be taken on in the near future, as well as reserve to guard against the ordinary break downs and interruptions in service.

Classification as to Use

The next decisions of interest affecting our work of inventory and appraisal are those of the Norfolk and Western Railroad Company v. Conley, et al, and the Northern Pacific Railroad v. the State of North Dakota. The effect of these decisions is to require different rates for classes of service where the costs are greatly different. The basis for differential rates is found in one of the earliest Supreme Court decisions in which it was held that "what the company was entitled to was a fair return upon the value of that which it devoted to the public use" but the Court went on to say that what the purchaser was entitled to was "service at no more than the worth to him." This decision practically confirmed the railroads in their existing practises of having different rates for different classes of service. With regard to electric lighting and power companies, it has been customary to classify customers in accordance with their requirements for service. This classification, however, was based on and adhered more or less closely to the cost for the respective classes of service.

Result

The result of the above mentioned decisions is that the inventories and the resulting appraisals must be classified in accordance with the use and the extent of the use. So far as the engineer is primarily concerned with cost, the inventory and appraisal will arrive at the same aggregate in any case, but the engineer is further concerned with the use and operation of the electrical property and it is the duty of the engineer to determine to what extent each class of property is required in the service of the public and to what extent it is required for the furnishing of the various classes of service. In preparing our inventory, therefore, such classifications must be made as will readily show the use to which the property is devoted. In the determination of rates it becomes especially important when it is recognized that charges for municipal street lighting have almost invariably been lower than the proper proportionate costs for this class of service, and where a company has been reasonably successful in carrying on its business it follows that the rates charged for other classes of service have been too high and the recent Court decisions* forbid the collecting from one class of customers any unreasonable portion of that which ought to be collected from other classes of customers, and further forbids the lowering of rates for reasons of public policy.

As to the calculations for depreciation, while the Idaho decision is to the general effect that full or theoretical depreciation should not be deducted in obtaining the fair value of the property, it cannot be said that this principle is at all well established, and it becomes necessary, in our inventory, to determine the accrued depreciation of each item, taking into account not only ordinary wear and tear, but obsolescence and inadequacy (which some authorities call functional depreciation). The writer has long been of the opinion that in order to square our valuations with the Court decisions, we must (1) obtain definite appraisals of the existing physical property, (2) ascertain the full theoretical depreciation, (3) make such deductions as are necessary because of property built unwisely or for anticipated increases in population which have not materialized or for classes of service which have not been taken on. In other words, our valuation must be determined by using our best present-day judgment as to the amount and classes of property required to serve the customers now connected and those which may be connected within a reasonable future period. This may even involve an addition for property not now in place, but which ought to be in place in order to assure continuity of service with the requirement that same be installed. In addition, however, to the value of the physical property, the writer desires to take refuge behind the words of Justice Harlan when he says, "We do not say that there may not be other matters to be regarded in estimating the value of the property." It is the writer's contention that in making the appraisal of the physical property, due allowance must be made for overhead charges. The writer's opinion on this phase of the matter has already been expressed in a written discussion which appeared at the San Francisco

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*See Norfolk & Western & North Dakota cases cited above.

Convention of the Institute in 1915. In addition, however, there are allowances for various intangibles not properly included under the head of overhead charges. They are (1) cost of organization and obtaining the necessary charters and franchises, (2) deficits in operation in the early history of the project, (3) lack of profits in the later years and (4) the unearned depreciation which has accrued. It is the writer's further opinion that the aggregate of these elements ought to bear some favorable relation to the total value of the physical property, but it is the province of the engineer to investigate and determine the various items referred to with the exception, perhaps, of items concerning the cost of organization and obtaining the necessary charters and franchises. All other elements in determining the appraisal and valuation of a public utility property and in the determination of the deficits, lack of profits or otherwise, are matters solely within the province of the engineer.

The above items should be considered as making up the "cost of establishing the business." There has been much contention with reference to the necessity of including "going value" but here again we are confusing cases involving justice to the investor with "purchase and sale" cases. "Going value" is an element to be considered in "purchase and sale" cases and has no pertinency whatever in rate cases. The United States Supreme Court, in its recent decision regarding the Des Moines gas rates, decided that "going value" was to be considered in these cases, but based its estimates of "going value" on those elements which go to make up the "cost of establishing the business." In the determination of reasonable or fair rates, full consideration must be given to the sacrifice made by the investor. This will include, in addition to the investment in the physical property, early losses, lack of profits and unearned depreciation, the aggregate of which should be classified as the "cost of establishing the business."

CONCLUSIONS

1. Property must be inventoried in such detail as will lead to a determination of its value or cost within a very small percentage of absolute accuracy.

2. It must be classified as to its use and as to the degree of its use in the various classes of service.

3. The inventory must include full information as to age and present condition, this information leading to accurate estimates of accrued depreciation.

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CONTINUOUS INVENTORIES: THEIR PREPARATION AND VALUE

BY HARRY E. CARVER

ABSTRACT OF PAPER

Due to enactment of laws in various states requiring approval of State Commissions before issue of securities, and due to other conditions, there has arisen a demand for a continuous inventory of property owned by utility companies.

First section of this paper discusses the advisability of attempting such an inventory, giving possible uses and advantages to be derived therefrom, and the second section discusses the preparation of such an inventory, suggests the division of the property into four general groups for the purpose, and outlines general forms and methods for collecting and recording data required.

AMONG papers presented at the Pacific Coast Convention of the Institute at San Francisco in 1915, under the general heading of a *Symposium of Inventories and Appraisals of Properties*, was one by Mr. W. G. Vincent, Jr., in which the subject of keeping inventories and appraisals up to date was treated in some detail. In the discussion which ensued, it seemed to be the opinion that the amount of detail and extra work and expense which would be incurred by a company's operating force, would be too great to make it advisable or practicable to do this. At least one of the large public utility companies under the jurisdiction of the New Jersey Commission, namely one of the telephone companies connected with the Bell system, is apparently accomplishing this with an expenditure of labor and other expense which is apparently within reason, and both the New Jersey and New York Commissions are endeavoring to develop methods for keeping inventories up to date in which it is hoped that the co-operation and approval of public utility companies in general may be secured.

DISCUSSION OF THE VALUE AND USE OF A CONTINUOUS INVENTORY

The desirability and the purposes for which an inventory and appraisal of a company's property is made have been generally discussed heretofore and the necessity of making such an inventory and appraisal under certain conditions is probably sufficiently apparent to eliminate the necessity of further discussion on this matter. Such inventory and appraisal of any large company is comparable to a general census which it has been customary to make at periodical intervals for centuries. If it were necessary or advisable to have the results of an up to date census available at frequent intervals the question would doubtless arise as to the desirability of keeping a complete census of all the people in the country up to date by other means than going out and counting them every five or ten years.

In the same way, if it is advisable or necessary to have available a total inventory and appraisal of a company's property at frequent intervals of time, it would seem advisable to consider the problems involved in maintaining such an inventory at all times.

If this kind of an inventory would serve no other purpose than in making data readily available for the compilation at any time of a total inventory and appraisal of the company's property, then the feasibility of doing so depends upon at least four factors.

1. The frequency with which it may be desirable.
2. The additional yearly expenditure required, multiplied by the number of years intervening compared with the cost of obtaining the results by a complete new inventory at a later period.
3. The comparative accuracy of an inventory by the two methods and the accuracy which is liable to be required in future appraisals.
4. The speed with which it may be desirable to compile the same.

A consideration of the frequency with which complete inventories are liable to be required leads to the conclusion that they are liable to occur much oftener in the future than in the past, as the custom of requiring yearly reports to various tax commissions and government regulating commissions appears to be becoming much more general and required in more detail than heretofore.

A consideration of the other factors involved in keeping a continuous inventory brings to light a number of other reasons and advantages to be obtained by carrying out such an undertaking. Besides the company itself, considered as a unit, there are at least three other classes of people who are interested in the operation of a public utility corporation.

1. The patrons or customers of the company.
2. The investors in the company's securities.
3. The general public, including the various governmental agencies representing this public.

A perpetual inventory of a company's property would be useful to any company in the following ways:

1. Data are made available for answering any complaints as to discrimination or overcharges in existing rates and the company should be able to present promptly a full statement of facts on the basis of which a satisfactory determination can be made.

2. The increased cost of labor and material renders it probable that many rate cases in the future will involve increases, rather than decreases in rates for services rendered and the company will need to be fortified with all necessary facts as to the cost of service rendered, among which are included as two of the principle items, a fair return on the investment and a yearly allowance toward a reserve fund for replacing the property involved, at the time that such replacement is needed.

3. In many rate cases and cases pertaining to security issues, inventories and appraisals have been made and depreciation and present value estimated. Various methods have been used for making these determinations and estimates of future depreciation have been made. There the matter, in most cases, has been dropped and the future depreciation has been left to take care of itself.

The cut and dried formulas for determining depreciation used in many cases have often been challenged and criticized. The criticism has been so severe that it is not at all unlikely that new methods will be adopted in the future which will depend upon changes which actually take place as time goes on and that will have to be checked up from time to time. Probably the surest check upon accruing depreciation or an accruing renewal fund is a comparison of the fund with the total cost of the property, subject to depreciation, which, of course, can only be made by having at hand an up to date inventory. It is quite probable that, in the future, one of the most urgent reasons for making an inventory and keeping it up to date will be the necessity of having some means for judging whether or not a company is making reasonable preparation for renewing and perpetuating its property.

4. For most public utility companies, the approval of a State Commission is necessary for the issue of new securities. The labor and time involved in securing the approval of the same, both on the part of the company and of the Commission, would be materially reduced. There would be less interruption of the work performed by the operating force of the company from governmental inspectors, either in checking up construction expenditures for new securities or in making a complete appraisal of a company's property for this or other purposes.

5. The market for a company's securities would, doubtless, be increased by a general knowledge that a running inventory of all the company's property was maintained and consequently that some check was available upon the total property represented by securities issued and on the accounting methods followed by the company.

6. It would probably make available data for securing franchise extensions from various municipalities under more equitable terms than appears to be possible at present.

7. Data would be available for making investigations to satisfy the demands of labor employed in the company's operations as to whether they were, or were not, receiving a fair proportion of the company's revenue. One of the reasons privately advanced by labor union men for demanding an increased share in a company's revenue is that the books of many companies are kept in such a manner that the revenues are covered up in some way and their total income is not shown in the reports made to the stockholders or public bodies. Without commenting on the merits of this contention, it is probable that the means of proving or refuting it would be much more readily available than at the present time.

8. It is the general experience in checking up the books of various companies in New Jersey for approval of construction expenditures that comparatively little question can be raised as to the total amounts claimed, but that the distribution to the various items or accounts by which the expenditures are classified, are very frequently incorrect, which fact is generally brought out by making an inventory of the property acquired and checking up the unit prices. Hence there seems little doubt that a continuous inventory maintained by a company would be conducive to much more accurate accounting and distribution of charges between fixed capital and operating expenses as well as a more accurate distribution of general overhead charges than is possible at present.

9. Insurance adjustment for fire and other losses could be more readily and equitably obtained.

10. Tax Commission reports and yearly reports to regulating bodies could be more readily compiled.

11. At the present time a few large companies are keeping a more or less detailed record as to the location of their various items of property, especially of underground conduits, etc. Many companies, however, have very incomplete records as to just what they own or where it is located and information is not readily available as to what service they are able to render at a given location, either permanently or temporarily. As an illustration of this point, the case may be cited of a gas company which was recently called upon for service by a prospective customer in an outlying district. An employee of the company, to whom the request was made, replied that the company would be unable to make the connection to the customer's premises, as the company's mains were too far away. Later investigation proved that the company had a service connection to the house next door and that the main in the street extended to within about fifty feet of the prospective customer's lot. A continuous inventory would necessitate the keeping of records which would prevent these or similar occurrences.

12. In addition to requiring records which would give the location of property owned, the adoption of such a system in connection with a continuous inventory and appraisal would be of great value in promoting more efficient construction and operation, as detailed costs would readily be available from which the costs of rendering any particular service or of making any particular extension or betterment could be accurately determined.

Some of the advantages cited above would apply equally well to the company's customers, investors, and the public, but the above seem to be sufficient.

PREPARATION OF THE INVENTORY

This subject apparently implies first a complete inventory and appraisal of the property as of a given date but this is not a necessary prelude to the above, and, as most companies have not a complete inventory and appraisal of their property, it seems advisable to state that a company can readily start an inventory of all new property acquired from the present time forward and all old property withdrawn from service and either replaced or abandoned, without detailing a special force of engineers to make a complete inventory of all property. The record of the company's property in existence at the time the inventory is started can be obtained at such times as the company's engineers and accountants may be available for this work, and, in the course of a few years it might be possible in this manner to obtain a complete inventory.

The actual problem of maintaining a continuous inventory resolves itself into the question as to how small the units may be into which a property may be divided and records kept without an unreasonable expense, and how large the units of property may be taken without making indentification of any item or part of the property so uncertain as to destroy the accuracy of the inventory and subsequent changes in the capital account.

To illustrate, suppose a company builds today a large power station and ten years from now it builds an addition, removing one wall and making use of some of the material for the new work. Or, a company builds an overhead distribution system; five years later it becomes necessary to replace some of the existing wires on a certain street with a larger size; ten years later it is necessary to move a part of this same line to the other side of the street and install joint poles with another company, and fifteen years later it becomes necessary to replace all this construction with an underground system.

Is it possible to keep an accurate record of these transactions so that the capital account shall record the cost of the additions and the proper withdrawals in going through these various changes without relying on estimates of both quantities and costs to such an extent as to render the records questionable as to their accuracy? Heretofore it has been necessary to rely largely on estimates of the original cost of both labor and material in recording such transactions; but, with proper co-ordination and co-operation of the various departments concerned, we believe that the necessity of making estimates can largely be obviated, and the total cost installed in place at any particular period of time obtained without any great expense.

The fundamental requirement for accomplishing the above is an efficient "work order" system, also quite generally known under the head of "Authorizations for Expenditure" or some similar name. A work order system is in force in practically every company of appreciable size today, and with more or less modification can be adapted to give the records required.

In order to obtain the necessary records for writing off the original cost of the property when it is retired, it is absolutely necessary that one additional step be added to this system as it is generally in force in most companies; viz, *an allocation of the cost of each piece of construction or property acquired must be made in detail when the work is completed, and preferably just before the work order is finally closed*, as such an analysis will frequently disclose inaccuracies in either debits or credits. This practise is followed by many companies to a certain extent at the present time, but must be applied to all work orders, and the final cost must be reduced to the same units that are liable to be needed in making estimates for withdrawals or additions. Unless the property acquired is going to last forever or be withdrawn from capital account as a unit, such an estimate must be made sometime, and there would seem to be no time when a more accurate analysis could be made than at the time the work is done or property acquired.

An analysis of costs made at this time would aid in checking up inaccurate distribution of labor and material, and it is very important to do this, as the fact must be recognized that all of these records are going to depend primarily for their accuracy on the proper distribution of labor and material by the construction foreman, and especial emphasis must be laid on this point.

Many companies are keeping at the present time an additional set of records which can be made to fit in nicely with a continuous or perpetual inventory. These records consist mostly of cards showing the location, type, size, and dates of installation, change in location, etc., of meters, transformers, poles and attachments, and possibly, in some cases, street lamps, services and similar items. As stated in the first section of this paper, such records are valuable for other than strictly inventory purposes but they are also essential for this purpose in connection with the forms suggested below.

The items of property for the purposes of inventory may be divided into four general groups as follows:

A. Those items which are large enough to be recorded individually or in small groups with one entry, but which are liable to be altered or changed in part; *e.g.*, buildings.

B. Items which may be recorded individually and which are withdrawn from service as a unit; *e.g.*, meters.

C. Items which must be recorded in units of length, pounds, or some similar units and miscellaneous items; *e.g.*, wires and cables, insulators, arresters, etc.

D. Those items of property which are usually carried in inventories at the present time and which are usually checked up by field inventory at regular intervals; *e.g.*, materials and supplies portable tools, office furniture, etc.

There may be considerable difference of opinion as to just what method should be followed in collecting the data required, but a general scheme could be followed for either a gas, electric, railway or railroad, telephone or telegraph, water or sewer utility or a private industrial plant by classifying the property in the general groups indicated above about as follows:

A. 1. Land and right of way.
   2. Building and structures.
   3. Equipment of stations, buildings, etc.

B. Poles, transformers, meters and services for an electric company; meters, services, fire hydrants, lamps, etc. for a water or gas company and similar items for these or other companies.

C. Wires, cables, conduits, crossarms, insulators, for an electric company; feeder cable, trolley wire, straight track, etc., for railways; transmission and distribution mains for water, gas and sewer companies.

D. Office equipment, shop equipment, stable equipment, etc.

FORMS FOR GROUP A

The general form of recording data for items in group A in detail is given on form 1.

These data should be obtained from the completion report of the work order, an extra copy of which it might be advisable to file with other inventory data.

The basis for estimating the unit prices for the cost of brick wall removed (mentioned on form 1) should be found in this completion report. A list of the quantities involved should be available from the information and plans in the hands of the engineer responsible for the new addition. With this information there should be need for very little estimating which is not based on actual facts.

The summary of all such property classified under any particular account for any particular division or subdivision could be recorded on form 2 and the totals for that account or division readily obtained by summing up the items, on such occasions as a total is desired, probably no oftener than once each year.

Form 1

AMERICAN ELECTRIC CO.—*Subsidiary Co*...............
DIVISION—Northern *LOCATION—14th St. Belleville* *File No.* 5
Computer..............*Checker*............*App'd by*....*Date*..*Acct. No.* 118
SUBJECT Substation Buildings............*Reference*...........*Sheet No.* 1
(*or other similar items in Group A*)

Auth. No. and page	Date acquired	Description—As originally acquired or of addition or withdrawal	Area—Size or No. of units	Original cost		Total cost corrected to date for additions, etc.	Est. remaining life
				Per unit	Total		
543-10	1911	1-Substation Building Brick on concrete fndn. Slate Roof, etc. 40′ × 30′ One Story & Basement.	1200 sq. ft. 20000 cu.ft.	$2.00 .12	$2400	$2400	50
1585-4	1916	Brick wall removed 30′x18′ High			200	2200	45
1586-4	1916	Addition 10′x40′	400 sq. ft. 6667 cu. ft.	2.50 .15	1000	3200	46.6

Explanatory Notes on Use of Form No. 1

Note 1—If any item of property subject to depreciation is acquired subsequent to date of first use, this fact should be indicated together with other information available as to original construction, date, cost, etc.

Note 2—Remaining life of 45 years is obtained by subtracting 5 years elapsed between 1911 and 1916 from 50 year life first estimated.

Remaining life of 46.6 years is obtained by computing a weighted average of $2200 at 45 years and $1000 at 50 years.

Note 3—Present value on a basis of straight line depreciation may be readily obtained by multiplying $3200 by ratio of 46.6 years to 50 years, giving 93.2% and $2982.

Form 2

AMERICAN ELECTRIC CO—*Subsidiary Co*...............
DIVISION Northern *LOCATION All* *File No.* 5
Computer........*Checker*......*App'd by*......*Date*.............*Acct. No.* 118
SUBJECT Summary of Substation Buildings, 1916 *Sheet No.* 101
(*or similar item in Group A*)

Ref. Sheet	Item	Location	Date originally acquired	Cost to Jan. 1	Added	Withdrawn	Cost to Dec. 31	Present value Dec. 31	
								%	Amt.
1	SS Building	14th St. Belleville	1911	$2400.	$1000	$200	$3200	93.2	$2982.
2	ditto	First St. Nutley	1906	etc.					
					Transferred to sheet No. 1-10				

Form 3

AMERICAN ELECTRIC CO.—*Subsidiary Co*..............
DIVISION Northern *LOCATION All* *File No.* 5
Computer....*Checker*....*App'd by*....*Date*.................... *Acc. No.* 124
SUBJECT 5-kw. Transformers Type X *Reference*.......... *Sheet No.* 1
(*or similar items in Groups B or C*)

Date	Ref. sheet	Number of units				Cost per unit	Total cost	Corrected total cost to date	Years	
		Added	Withdrawn		Net total to date				Av. Life units withdrawn	Av. age units installed
			No.	Date orig. installed						
Brought Fwd.		Invento	ry Ja	n.1,1916	250	$62	$15,500	$15,500		5.1
1916		40			290	61*	2,400	17,940		
1916			2	1900	288	65†	130†	17,810	16	
1916			3	1901	285	64†	192	17,618	15	
1916		Invento	ry D	ec. 31,	285	61.82		17,618		5.08
1917										

* Average costs for all units of this size for any given period—say one year.

† Prices might be averaged and one figure shown or, if not much variation in price, they might be withdrawn at the average cost of the 250 shown at the beginning of the year

Form 4 AMERICAN ELECTRIC CO.—*Subsidiary Co*............
DIVISION Northern *LOCATION All* *File No.* 5
Computer....*Checker*....*App'd by*....*Date*.................... *Acct. No.* 124
SUBJECT Summary of Transformers—1916 *Sheet No.* 101
(*or similar item in Group B or C*)

Ref. sheet	Size	Type	Number of units				Cost of units				Av. cost per unit Dec. 31	Present value Dec. 31	
			Jan. 1st.	Added	With-drawn	Dec 31	Jan. 1st	Added	With-drawn	ec. 31		%	Amt.
1	5 kw.	X	250	40	5	285	$15,500	$2,440	$322	$17,618	$61.82	4.6	$13.143
5	10 kw	X	100	20	2	118etc							

Transferred to sheet No. 1–10

Note:—"%" under "Present Value" for straight line depreciation would usually be obtained by comparing average age of units installed with average life of units withdrawn. In this case it is estimated that a 15 or 16-year life is not long enough and life base is arbitrarily taken as 20 years. In some cases it might be desirable to consider salvage in arriving at present value but it is disregarded above for sake of brevity.

FORMS FOR GROUPS B AND C

The same forms are recommended for both groups B and C, but the method of collecting the data required is different.

For both groups it is thought best to use unit costs averaged for the district into which the company chooses to subdivide its territory, say a tax district, and for a certain period of time, monthly, quarterly, or yearly. The average for labor, storeroom charges, miscellaneous material items, overhead charges, etc., would necessarily need to be computed after the close of the current period or the average taken from the preceding period and final adjustments made for variation.

The total quantities for all items in group B, for which a card record is assumed to be made, can be computed either from the cards or from the completion reports of the work orders. Probably the total could be obtained more readily from the card records, whether tabulated by hand or sorted and tabulated mechanically by means of the Hollerith system of card records.

For all items in group C, the totals of both quantities and prices would probably best be obtained and reconciled with the amounts given in the completion reports of all work orders involved, although they might be obtained from field books or street maps showing construction changes for the required period, or from pole record and manhole record cards which usually indicate the wires, cables, conduit, etc., extending to the adjacent units.

Form 3 shows method of recording a group of similar units, viz., 5-kw. transformers and Form 4 shows method of summarizing units of various sizes.

FORMS FOR GROUP D

Form 5 is recommended for summarizing items in this group as it is contemplated to include only such items as a company carries or could reasonably carry on an inventory which is usually made at the present time by actual count. This inventory as applied to office furniture, large portable tools, etc., usually gives the estimated present value of these items and they are carried into the property account each year at this depreciated value.

The first entry for each of these items is naturally the cost new and it is recommended that this cost new be carried in the inventory in a parallel column with the depreciated value until such time as the item is retired. Also, that the total cost new of

Form 5

AMERICAN ELECTRIC CO.—*Subsidiary Co*............
DIVISION Northern *LOCATION Belleville Office* *File No.* 5
Computer....*Checker*....*App'd by*....*Date*......................*Acct. No.* 107
SUBJECT General Equipment, Dec. 31, 1916 *Ref*...............*Sheet No.* 101
(*or similar items in Group D*)

Quantity	Unit	Item	Year acquired	Original cost			Present value	
				Ref.	Unit	Amt.	%	Amt.
2		Typewriters................	1914	52	$79	$158	75	$118
2		Typewriter desks...........	1912	35	20	40	80	32
6		Bent wood chairs...........	1916	Bill	3	18	100	18
		Totals, Dec. 31...........				$216	77.7	168
		Additions 1916.............				18		
		Total of items Jan. 1......				$198		
		Totals per inventory 12-31-15		61		210		
		Withdrawals 1916..........				$12		

Transferred to sheet No. 1–10.

Form 6

AMERICAN ELECTRIC CO.—*Subsidiary Co*.............
DIVISION Northern *LOCATION*..............................*File No.* 5
Computer....*Checker*....*App'd by*....*Date*......................*Acct. No.* 1
SUBJECT Grand Summary, 1916 *Sheet No.* 10

Acct. No.	Ref. Sheet	Item	Total cost				Present value	
			Jan. 1	Added	With drawn	Dec. 31	%	Amt.
101	5	Land, etc..................						
107	101	General Equipment.........	$210	$18	$12	$216	77.7	$168
118	101	Substation Bldgs...........	2400	1,000	200	3,200	93.2	2,982
124	101	Transformers..............	15,000	2,440	322	17,618	74.6	13,143
		Totals Northern Div. 1916	18,110	$3,458	$534	21,034	77.5	16,293

EXPLANATORY NOTES IN REFERENCE TO USE OF ABOVE FORMS.

Note 1. Loose leaf sheet 8½"x11" is recommended for all forms.

Note 2. For all withdrawals use red ink.

Note 3. Forms 1 and 3 constitute the continuous record. All other forms are made up when it is desired to arrive at totals and are correct for one date only. If periods used are different than calendar year, forms would be slightly modified.

Note 4. Provision for identifying computers, etc. on forms 1 and 3 after first entries could be made by having initials inserted in date column or by providing separate column.

Note 5. Figures carried to grand summary, form 6, are merely illustrative and not the totals which would be obtained if more entries were made on forms 2, 4, and 5.

Note 6. From totals on form 6, the amount of additions for which new securities may be issued may be readily determined.

Note 7. By comparing form 6 as filled out for 1915 with year 1916, the credit which must be made to reserve account from earnings to provide for the year's depreciation may be determined.

all items be carried in the property account; and that the estimated accrued depreciation of all such items should be carried in the depreciation reserve account instead of being charged directly to operation each year and lost sight of thereafter as is the practise with many companies today.

A comparison of such an inventory at the end of any year with the preceding will indicate the total value of all withdrawals and additions and a proper adjustment can then be made in one lump sum between the capital account and the depreciation reserve.

Form 6 is to be used as a summary of all property and probably needs no explanation in addition to notes given.

To carry out the above, it would seem advisable to create a separate department under the joint supervision of the chief engineer, general auditor or controller, and the official in charge of the Public Relations Committee of a utility if such a committee exists. The man in charge of this department should understand both engineering, accounting and statistical work, and be capable of co-operating with all other departments of the company to secure the full benefits possible to be derived as outlined in the first section of this paper.

The methods indicated above would necessarily need to be modified to suit the needs of any individual company, and in actually working out the same, it is probable that some modifications of the present system of records and accounting could be adopted which would materially lessen the amount of additional work which might appear to be necessary at first glance in inaugurating such a system of continuous inventory and appraisal.

Presented at the 326th meeting of the American Institute of Electrical Engineers, New York, November 10, 1916.

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GROWTH AND DEPRECIATION

BY JULIAN LOEBENSTEIN

Abstract of Paper

It is generally assumed that a complex utility property will depreciate to an approximately fixed per cent condition. This is shown by theoretical and actual curves to be incorrect. It is shown that the manner of the company's growth affects its per cent condition.

The necessity for reserves, the manner in which they may be kept and the return which should be allowed on them, whether reinvested or not, is discussed. Several Commission and Court decisions are quoted to show the tendency to disallow a return on a reserve and arguments are presented in refutation of the decisions.

The principal points are as follows:

1. The condition of a property is dependent not only on maintenance but also on its growth.
2. Property does not settle down to a fixed per cent condition.
3. Capital is kept intact by reinvesting reserve in extensions. Under this condition, depreciated value of the entire property is the fair one for rate making purposes.
4. For a company unable to use reserve in extensions a liquid depreciation fund will be necessary.
5. The same return, available for dividends, should be allowed on a reserve as on the remainder of the property.

IN THIS article the writer tries to bring out the following points:

First, to show that the per cent condition of any property is dependent not only upon the maintenance but upon the past and present growth.

Second, to show that under practically no condition will it be necessary to bring a property back to one hundred per cent condition, but that it does not settle down to some fixed per cent condition less than one hundred per cent. It does, however, go through a repeating cycle of conditions, one point in the cycle being a maximum above which it will never rise. This maximum point will depend entirely upon the growth of the property and should be studied separately for each property under consideration.

Third, to show that under certain conditions of growth, a growing company need keep no liquid depreciation reserve fund; that it may reinvest the reserve in extensions, making renewals as they come due in any given year, from the amount set aside for depreciation reserve in that year, and that by so doing the stockholders' capital is kept intact, yet the depreciated value of the whole property is the fair one, both for consumer and stockholder, for rate-making purposes.

Fourth, to show that for a company which has stopped growing or for one which is growing at a rate not large enough to use all of the depreciation reserve for reinvestment in extensions, it will be necessary to have a continually varying amount in a liquid depreciation reserve fund, and that this amount will fluctuate in a manner depending upon the company's growth.

Fifth, to show that since such a liquid reserve may be necessary for a growing company and will be necessary for a company which has ceased to grow, that the same return should be allowed on such a reserve as on any other capital invested in the property, and that such return should be available for dividends, provided that the cost new, less depreciation, is to be used as a basis for making the rates.

The following definitions and assumptions are made in the discussion. By liquid depreciation reserve fund is meant a reserve either as cash in a bank, invested in bonds or employed in any other way so as to be readily convertible into cash for immediate use. This is to distinguish it from depreciation reserve, which is invested in extensions and betterments and which cannot be readily turned into available cash. No consideration is taken of scrap value nor of a reserve for emergencies or catastrophies as the calculations are not in any way affected by such a fund, the effect being simply to refer them to a different ordinate. All calculations are on the straight line basis and all properties considered are assumed to be kept in the best state of repair. It is assumed that the depreciated value of the property will be used as a basis for making the rates.

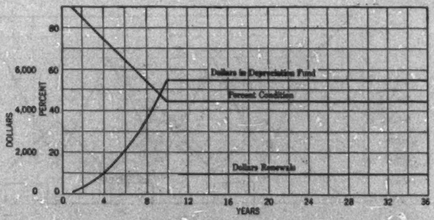
Before attempting to draw any conclusions from the tables, it is advisable to show how they were constructed and calculated. Table I is the calculation for a property in which a uniform capital investment of $1000 a year is made for ten years and the property then stops growing. All the elements of the property are assumed to have a ten year life. Table II shows a property similar in all respects but one, to that shown in Table I. In Table II the uniform investment is made for only five years of the ten. Table III is for a property the elements of which have a ten year life. In the first year the capital investment is $1000. In the second year the depreciation fund is used for investment in extensions and enough additional capital is invested to bring the investment of both capital and reserve for the year, up to $1000. The same procedure is followed each

TABLE I.

UNIFORM YEARLY INVESTMENT FOR TEN YEARS

End of Growth—Tenth Year
Life—Ten Years
Depreciation reserve not invested in extensions

End of year	Capital invest. for the year	Total capital expenditures	Increment to Depr. fund	Deduction from depr. fund	Total in depr. fund	Percent condition
1	1000	1,000	100	0	100	90
2	1000	2,000	200	0	300	85
3	1000	3,000	300	0	600	80
4	1000	4,000	400	0	1000	75
5	1000	5,000	500	0	1500	70
6	1000	6,000	600	0	2100	65
7	1000	7,000	700	0	2800	60
8	1000	8,000	800	0	3600	55
9	1000	9,000	900	0	4500	50
10	1000	10,000	1000	0	5500	45
11	—	10,000	1000	1000	5500	45
12	—	10,000	1000	1000	5500	45
13	—	10,000	1000	1000	5500	45
14	—	10,000	1000	1000	5500	45
15	—	10,000	1000	1000	5500	45
16	—	10,000	1000	1000	5500	45
17	—	10,000	1000	1000	5500	45
18	—	10,000	1000	1000	5500	45
19	—	10,000	1000	1000	5500	45
20	—	10,000	1000	1000	5500	45



CURVE I—UNIFORM INVESTMENT FOR TEN YEARS

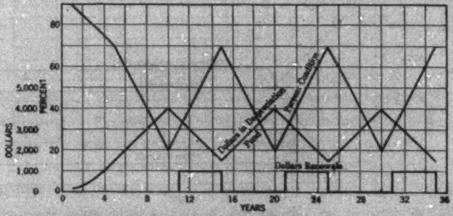
End of growth, tenth year—life, ten years—depreciation reserve not invested in extensions.

year until at the end of the tenth year the property ceases to have any further additions. Table IV is for a property the elements of which have a ten year life. Starting with an investment of $1000 the first year, the investment decreases one hundred dollars per year until the tenth year, at which time the property stops growing. The depreciation reserve is not re-

TABLE II.

Uniform yearly investment for five years
End of growth—fifth year
Life—ten years
Depreciation reserve not invested in extensions

End of year	Capital invest. for the year	Total capital expenditures	Increment to depr. fund	Deduction from depr. fund	Total in in depr. fund	Percent condition
1	1000	1000	100	0	100	90
2	1000	2000	200	0	300	85
3	1000	3000	300	0	600	80
4	1000	4000	400	0	1000	75
5	1000	5000	500	0	1500	70
6	—	5000	500	0	2000	60
7	—	5000	500	0	2500	50
8	—	5000	500	0	3000	40
9	—	5000	500	0	3500	30
10	—	5000	500	0	4000	20
11	—	5000	500	1000	3500	30
12	—	5000	500	1000	3000	40
13	—	5000	500	1000	2500	50
14	—	5000	500	1000	2000	60
15	—	5000	500	1000	1500	70
16	—	5000	500	0	2000	60
17	—	5000	500	0	2500	50
18	—	5000	500	0	3000	40
19	—	5000	500	0	3500	30
20	—	5000	500	0	4000	20



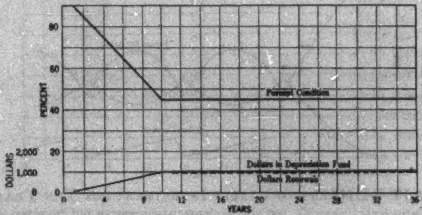
CURVE II—UNIFORM YEARLY INVESTMENT FOR FIVE YEARS

End of growth, fifth year—life, ten years—depreciation reserve not invested in extensions.

TABLE III.

Uniform yearly investment for ten years
End of growth—tenth year
Life—ten years
Depreciation reserve invested in extensions

End of year	Capital Invest. for the year	Total capital expenditure	Investment for the year from depr. reserve	Total investment capital plus reserve	Increment to depr. fund	Deduction from depr. fund	Total in depr. fund	Percent condition
1	1000	1000	—	1,000	100	—	100	90
2	900	1900	100	2,000	200	100	200	85
3	800	2700	200	3,000	300	200	300	80
4	700	3400	300	4,000	400	300	400	75
5	600	4000	400	5,000	500	400	500	70
6	500	4500	500	6,000	600	500	600	65
7	400	4900	600	7,000	700	600	700	60
8	300	5200	700	8,000	800	700	800	55
9	200	5400	800	9,000	900	800	900	50
10	100	5500	900	10,000	1000	900	1000	45
11	—	5500	—	10,000	1000	1000	1000	45
12	—	5500	—	10,000	1000	1000	1000	45
13	—	5500	—	10,000	1000	1000	1000	45
14	—	5500	—	10,000	1000	1000	1000	45
15	—	5500	—	10,000	1000	1000	1000	45
16	—	5500	—	10,000	1000	1000	1000	45
17	—	5500	—	10,000	1000	1000	1000	45
18	—	5500	—	10,000	1000	1000	1000	45
19	—	5500	—	10,000	1000	1000	1000	45
20	—	5500	—	10,000	1000	1000	1000	45



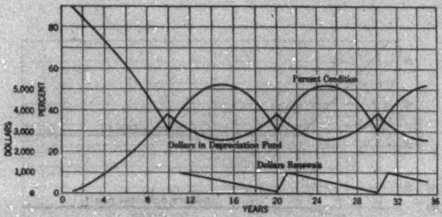
CURVE III—UNIFORM YEARLY INVESTMENT FOR TEN YEARS
End of growth, tenth year—life, ten years—depreciation reserve invested in extensions.

invested. Table V shows a property consisting of two life groups having lives of ten and twenty years respectively. Starting with a capital investment of five hundred dollars for each of

TABLE IV.

Decreasing yearly investment for ten years
End of growth—tenth year
Life—ten years
Depreciation reserve not invested in extensions

End of year	Capital invest for for the year	Total capital expenditure	Increment to depr. fund	Deduction from depr. fund	Total in depr. fund	Depreciated value of property	Percent condition
1	1000	1000	100	—	100	900	90.0
2	900	1900	190	—	290	1610	84.6
3	800	2700	270	—	560	2140	78.3
4	700	3400	340	—	900	2500	73.6
5	600	4000	400	—	1300	2700	67.5
6	500	4500	450	—	1750	2750	61.0
7	400	4900	490	—	2240	2660	54.3
8	300	5200	520	—	2760	2440	47.0
9	200	5400	540	—	3300	2100	38.9
10	100	5500	550	—	3850	1650	30.0
11	—	5500	550	1000	3400	2100	38.2
12	—	5500	550	900	3050	2450	44.5
13	—	5500	550	800	2800	2700	49.1
14	—	5500	550	700	2650	2850	51.7
15	—	5500	550	600	2600	2900	52.8
16	—	5500	550	500	2650	2850	51.7
17	—	5500	550	400	2800	2700	49.1
18	—	5500	550	300	3050	2450	44.5
19	—	5500	550	200	3400	2100	38.2
20	—	5500	550	100	3850	1650	30.0



CURVE IV— DECREASING YEARLY INVESTMENT FOR TEN YEARS

End of growth, tenth year—life, ten years—depreciation reserve not invested in extensions.

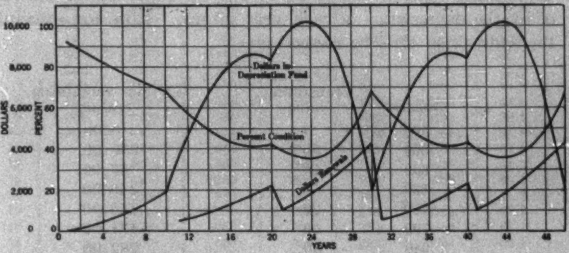
the groups, the capital investment is incrased one hundred dollars a year for each group for the ten years. In each year an equal amount has been reinvested in each life group, so that the total of such investments for any given year is nearly equal to the amount set aside in the depreciation reserve the year before. This continues up to and including the tenth year after which time further investments are discontinued, but renewals are made as each portion of the original investment reaches the end of its life.

It may be well here to point out something worthy of note which developed in the course of the calculation. It will be seen, by reference to Table V, that in every case, the sum of the dollars remaining in the fund (column 15) and the depreciated value of the property (column 17) giving (column 18) the total value of the property, is the same as the total capital expenditure (column 6). This furnishes a short method of calculating the depreciated value of the property *i.e.* by subtraction instead of by the depreciation of each year group. Take for example the tenth year: the long method is:—

Dollars	Per cent remaining value	Dollars remaining value
500	0	0.00
500	50	250.00
630	10	63.00
630	55	346.50
790	20	158.00
790	60	474.00
940	30	282.00
940	65	611.00
1100	40	440.00
1100	70	770.00
1300	50	650.00
1300	75	975.00
1500	60	900.00
1500	80	1200.00
1700	70	1190.00
1700	85	1445.00
1950	80	1560.00
1950	90	1755.00
2150	90	1935.00
2150	95	2042.50
		$17,047.00

This $17,047, the depreciated value of the property, as obtained above, plus $1953, the dollars in the depreciation fund, is equal to the total capital expenditure of $19,000. The short method is therefore, to subtract the dollars in the depreciation fund from the total capital expenditure to get the depreciated value of the property. This method was followed in the calculation of the table.

It is generally considered that a property maintained in good operating condition will be between 70 and 85 per cent new. In fact, Whitten, in his Valuation of Public Service Corporations, discussing depreciation says, (Vol. I, page 358, par. 421) "It has been stated that a street railway maintained in good operating condition will necessarily show cost less depreciation of from 70 to 85 per cent of the cost new". That this is an entirely fallacious assumption and that the percent condition of any property is not only a function of its maintenance, but also most decidedly of the manner of its growth, is shown by the accompanying tables and curves.



CURVE V—INCREASING YEARLY INVESTMENT FOR TEN YEARS

Life { one group, ten years
one group, twenty years

End of growth, tenth year—depreciation reserve invested in extensions.

It is now an easy matter to prove that Mr. Whitten's assumption is wrong, and also to prove the first point, which is that the per cent condition of any property is dependent not only on the maintenance, but upon the past and present growth. Referring to the tables, we see that in Table I and Curve I, where there has been a uniform investment over a term of years corresponding to the life of the property, the per cent condition varies from 90 to 45 during that term, and then stays at 45 when the property stops growing. The per cent condition appears as 45 instead of the proverbial 50 because, in the calculations, the end, instead of the beginning of the tenth year is considered. In Table II and Curve II, where there is a uniform investment

TABLE V

INCREASING YEARLY INVESTMENT

LIFE { ONE GROUP TEN YEARS
{ ONE GROUP TWENTY YE

END OF GROWTH TENTH YEAR

DEPRECIATION RESERVE INVESTE

End of year	Capital investment for the year		Investment for the year from depr. fund		Renewals		Total capital expenditure		Total capital expenditure both groups	Total investment from depr. fund		Grand total expenditure for either 10 or 20 year group	Grand total expenditure on property exclusive of renewals	Total expendit year
	10 year life group	20 year life group	10 year life group	20 year life group	10 year life group	20 year life group	10 year life group	20 year life group		10 year life group	20 year life group			10 year life group
No. 1	No. 2a	No. 2b	No. 3a	No. 3b	No. 4a	No. 4b	No. 5a Sum of No. 2a's	No. 5b Sum of No. 2b's	No. 6 No. 5a + No. 5b	No. 7a Sum of No. 3a's	No. 7b Sum of No. 3b's	No. 8 No. 5a + No. 7a	No. 9 2 × No. 8	No. 10a No 2a + No. 3a
1	500	500	—	—	—	—	500	500	1000	30	30	500	1000	500
2	600	600	30	30	—	—	1100	1100	2200	120	120	1130	2260	630
3	700	700	90	90	—	—	1800	1800	3600	260	260	1920	3840	790
4	800	800	140	140	—	—	2600	2600	5200	460	400	2860	5720	940
5	900	900	200	200	—	—	3500	3500	7000	760	760	3960	7920	1100
6	1000	1000	300	300	—	—	4500	4500	9000	1160	1160	5260	10520	1300
7	1100	1100	400	400	—	—	5600	5600	11200	1660	1660	6760	13520	1500
8	1200	1200	500	500	—	—	6800	6800	13600	2310	2310	8460	16920	1700
9	1300	1300	650	650	—	—	8100	8100	16200	3060	3060	10410	20820	1950
10	1400	1400	750	750	—	—	9500	9500	19000	3060	3060	12560	25120	2150
11	—	—	—	—	500	—	9500	9500	19000	3060	3060	12560	25120	—
12	—	—	—	—	630	—	9500	9500	19000	3060	3060	12560	25120	—
13	—	—	—	—	790	—	9500	9500	19000	3060	3060	12560	25120	—
14	—	—	—	—	940	—	9500	9500	19000	3060	3060	12560	25120	—
15	—	—	—	—	1100	—	9500	9500	19000	3060	3060	12560	25120	—
16	—	—	—	—	1300	—	9500	9500	19000	3060	3060	12560	25120	—
17	—	—	—	—	1500	—	9500	9500	19000	3060	3060	12560	25120	—
18	—	—	—	—	1700	—	9500	9500	19000	3060	3060	12560	25120	—
19	—	—	—	—	1950	—	9500	9500	19000	3060	3060	12560	25120	—
20	—	—	—	—	2150	—	9500	9500	19000	3060	3060	12560	25120	—
21	—	—	—	—	500	500	9500	9500	19000	3060	3060	12560	25120	—
22	—	—	—	—	630	630	9500	9500	19000	3060	3060	12560	25120	—
23	—	—	—	—	790	790	9500	9500	19000	3060	3060	12560	25120	—
24	—	—	—	—	940	940	9500	9500	19000	3060	3060	12560	25120	—
25	—	—	—	—	1100	1100	9500	9500	19000	3060	3060	12560	25120	—
26	—	—	—	—	1300	1300	9500	9500	19000	3060	3060	12560	25120	—
27	—	—	—	—	1500	1500	9500	9500	19000	3060	3060	12560	25120	—
28	—	—	—	—	1700	1700	9500	9500	19000	3060	3060	12560	25120	—
29	—	—	—	—	1950	1950	9500	9500	19000	3060	3060	12560	25120	—
30	—	—	—	—	2150	2150	9500	9500	19000	3060	3060	12560	25120	—

7

ENT FOR TEN YEARS

RS

YEARS

R

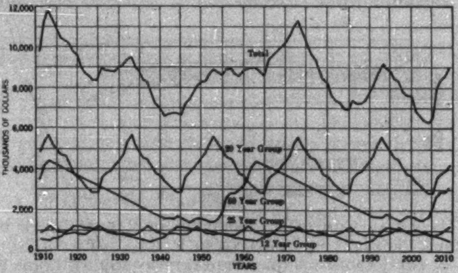
STED IN EXTENSIONS

nditure for the year	Increment to depr. fund for the year		Total increment for the year to depr. fund	Deduction for the year from depr. fund		Difference	Total remaining in depr. fund	Percent condition	Depreciated value of the property	Total value of the property
20 year life group	10 year life group	20 year life group		For extensions	For renewals					
No. 10b No. 2b + No. 3b	No. 11a $\frac{\text{No. 8}}{10}$	No. 11b $\frac{\text{No. 8}}{20}$	No. 12 No. 11a + No. 11b	No. 13a No. 3a + No. 3b	No. 13b No. 4a + No. 4b	No. 14 No. 12 — No. 13	No. 15 No. 12 + No. 14	No. 16 $\frac{\text{No. 17}}{\text{No. 9}} \times 100$	No. 17 No. 6 — No. 15	No. 18 No. 15 + No. 17
500	50.	25.00	75.00	—	—	+ 75.00	75.00	92.5	925.00	1000
630	113.	56.50	169.50	60	—	+ 109.50	184.50	89.0	2015.50	2200
790	192.	96.00	288.00	180	—	+ 108.00	292.50	85.8	3307.50	3600
940	286.	143.00	429.00	280	—	+ 149.00	441.50	83.0	4758.50	5200
1100	396.	198.00	594.00	400	—	+ 194.00	635.50	80.4	6364.50	7000
1300	526.	263.00	789.00	600	—	+ 189.00	824.50	77.8	8175.50	9000
1500	676.	338.00	1014.00	800	—	+ 214.00	1039.50	75.1	10160.50	11200
1700	846.	423.00	1269.00	1000	—	+ 269.00	1307.50	72.5	12292.50	13600
1950	1041.	520.50	1561.50	1300	—	+ 261.50	1569.00	70.8	14631.00	16200
2150	1256.	628.00	1884.00	1500	—	+ 384.00	1953.00	67.8	17047.00	19000
—	1256.	628.00	1884.00	—	500	+ 1384.00	3337.00	62.4	15663.00	19000
—	1256.	628.00	1884.00	—	630	+ 1254.00	4591.00	57.3	14409.00	19000
—	1256.	628.00	1884.00	—	790	+ 1094.00	5685.00	53.0	13315.00	19000
—	1256.	628.00	1884.00	—	940	+ 944.00	6629.00	49.3	12371.00	19000
—	1256.	628.00	1884.00	—	1100	+ 884.00	7513.00	45.8	11487.00	19000
—	1256.	628.00	1884.00	—	1300	+ 584.00	8097.00	43.6	10913.00	19000
—	1256.	628.00	1884.00	—	1500	+ 384.00	8481.00	42.0	10510.00	19000
—	1256.	628.00	1884.00	—	1700	+ 184.00	8665.00	41.0	10335.00	19000
—	1256.	628.00	1884.00	—	1950	— 66.00	8599.00	41.8	10401.00	19000
—	1256.	628.00	1884.00	—	2150	— 266.00	8333.00	42.8	10667.00	19000
—	1256.	628.00	1884.00	—	1000	+ 884.00	9217.00	38.9	9783.00	19000
—	1256.	628.00	1884.00	—	1260	+ 624.00	9841.00	36.4	9159.00	19000
—	1256.	628.00	1884.00	—	1580	+ 304.00	10145.00	35.3	8855.00	19000
—	1256.	628.00	1884.00	—	1880	+ 4.00	10149.00	35.2	8851.00	19000
—	1256.	628.00	1884.00	—	2200	— 316.00	9833.00	36.4	9149.50	19000
—	1256.	628.00	1884.00	—	2600	— 716.00	9017.00	39.4	9883.50	19000
—	1256.	628.00	1884.00	—	3000	— 1116.00	7901.00	43.8	10999.00	19000
—	1256.	628.00	1884.00	—	3400	— 1516.00	6385.00	49.8	12515.00	19000
—	1256.	628.00	1884.00	—	3900	— 2016.00	4369.00	58.0	14531.00	19000
—	1256.	628.00	1884.00	—	4300	— 2416.00	1953.00	67.8	17047.00	19000

[LOEBENSTEIN]

over a term of years not corresponding to the life of the property, the per cent condition varies from 90 to 70, while the property is growing. After that it varies in repeating cycles from 70 to 20 and back to 70 again. This, of course, is an extreme case, but it shows the possibilities of variation. Table III and Curve III show the same characteristics as Table I, although in Table I there is no reinvestment of reserve, while in Table III there is. Table IV and Curve IV show a more complicated property than the others. Here the variation during the ten years the property is expanding, is from about 92 to about 67. It then goes through a repeating cycle whose period is twenty years, varying from 67 to 35 per cent and back again.

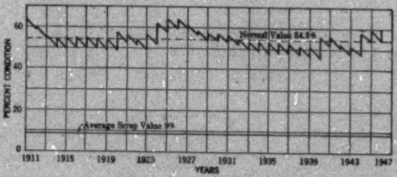
Thus it may readily be seen that a company which grows at an increasing rate will have a lower per cent depreciation in any given year, than a company which grows at a uniform rate, all other conditions being assumed the same. Furthermore, if both companies reach their maximum growth at the same time, thereafter their per cent condition will vary one from the other; first, because of the discrepancies between the terms over which the investments have been made and the life terms of the groups (compare Tables and Curves I and III) and second, because of the dissimilar manner in which the investments have been made (compare Tables and Curves IV and V).



CURVE VI—DEPRECIATED SERVICE VALUES OF AN ACTUAL PROPERTY

End of growth assumed Dec. 31, 1913—original service value $16,500,000—maximum per cent condition 69.0 per cent—minimum per cent condition 37.5 per cent.

Moreover this is borne out not only by the theoretical calculation, but Curve VI shows this condition for an actual electric property. The company was assumed to have reached its final growth on December 31st, 1913 after which date only renewals were made. The total service value of all the property was approximately $16,500,000 yet it may be seen from the curve that the actual service value varies from $6,200,000 to $11,000,000 or from 37.5 per cent to 69 per cent. Now, even supposing that some of the assumptions as to probable life are incorrect, the property will still vary over a wide range and not be in any popularly supposed fixed condition somewhere between 70 and 85 per cent. Curve VIII is for another actual property but a much smaller one than that considered in Curve VI. The property is assumed to reach its full growth in 1912, and the remaining service value is shown for the next 53 years. The service value varies from $810,000 to $370,000 or a corresponding per cent variation from 77 to 35.



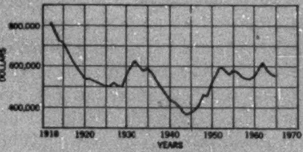
CURVE VII—TOTAL COMPOSITE THEORETICAL VALUE CURVE OF THE DEPRECIABLE PROPERTY OF THE UNITED RAILWAYS CO. OF ST. LOUIS AS GIVEN IN THE REPORT ON THAT PROPERTY BY THE ST. LOUIS PUBLIC SERVICE COMMISSION—1912

Before passing to point two, it is pertinent to quote again from Whitten, who says, (Vol. 2, page 1127, par. 1285). "We know, however, that there is a tendency for all utilities to settle down after a time to a more or less uniform condition as regards the percentage amount of accrued depreciation, and the annual requirements for renewals and replacements. After the various parts of a large public utility plant have gone through complete cycles of renewals, the plant settles down to a condition in which, saving extraordinary functional depreciation, expenditures for maintenance, repairs and renewals become practically constant. There is little fluctuation from year to year and the averages by five or ten year periods are practically identical. This settling down or equalizing process, is very greatly hastened by the fact that all large systems are constructed piecemeal."

The above theory, which the writer has tried to refute, is also supported by Mr. James E. Allison, Chief Engineer of the St. Louis Public Service Commission, who in the report on the United Railways Company of St. Louis, presents the curve which is here reproduced as Curve VII. He says, (Appendix A, page 89):

"It has been the purpose of the writer to show by diagrams that piecemeal built properties of any complexity, will eventually assume a theoretical value curve, closely conforming to the straight normal value line, halfway between 100 per cent and the composite scrap value of the property."

It cannot be denied that the curve which he gives most certainly is a uniform curve and tends to support his theory. It should be noted though, that even his curve varies over a range of 15 per cent during the comparatively short time of 13 years, and although 15 per cent is small, it takes a different aspect when considered as 15 per cent of $30,000,000, the approximate value of the property, or $4,500,000.



CURVE VIII—DEPRECIATED SERVICE VALUES OF AN ACTUAL PROPERTY

End of growth assumed Dec. 31, 1912—original service value $1,056,917—maximum per cent condition 77.0 per cent—minimum per cent condition 35.0 per cent.

As previously stated, the curve shown by Mr. Allison, is a remarkably smooth one, but when compared to Curves VI and VIII, it shows the danger of drawing a general conclusion from any one curve. Every complex property undoubtedly displays the tendency which Mr. Allison points out, but it would be decidedly unsafe to apply it indiscriminately to any property. The point is that each property should be investigated separately to determine its characteristics in this respect.

The second point, to show that under practically no condition will it be necessary to bring a property back to 100 per cent condition, has already been presented by many other writers, but it is given here again in conjunction with the conclusion from point number one. It is obvious that any property which has been built up gradually and not all at once, will have its various parts wear out in a similar sequence to that in which they were installed. Since different portions of the property will have to be replaced each year, it will never be necessary to replace all of them at once and so bring the property back to one hundred per cent condition.

As far as the point just made goes, most writers are agreed, but having reached that conclusion they claim that the property remains at a certain fixed condition, the exact per cent depending on the maintenance.

It is perfectly true that the entire property will not have to be renewed at any one time but only in the condition where there has been a uniform growth over a term of years corresponding to the life of the property (see Table I and Curve I) will the property reach a fixed condition and remain there after the property has stopped growing. Also, as long as a property is growing whether uniformly or otherwise, there will be a variation in its per cent condition. In other words, there is an obligation to renew varying amounts of property in different years in the future, and any calculation of reserves based on an assumption that because of perpetual life the company will reach a stable condition either during or after its growth is entirely incorrect.

It will be noticed from an examination of the tables that while the property is growing, the per cent condition is decreasing, the rate of decrease varying inversely with the rate of growth. When the property stops growing it has reached a certain per cent condition and thereafter it varies between that condition and some other, dependent upon the manner of growth. When the growth stops the property may be at a minimum per cent condition, as in Table IV and Curve IV, where there has been a decreasing rate of growth; or at a maximum as in Table V and Curve V where there has been an increasing rate of growth. Table IV and Curve IV show that the property will vary between 30 and 53 per cent, while Table V and Curve V show, in that case, a variation of from 35 to 68 per cent.

From the above figures it is evident that each property, should it stop growing, will go through a cycle in which it reaches a certain maximum condition less than 100 per cent, this maximum condition being entirely dependent on the manner of the property's growth.

It may be argued that the writer has made arbitrary and special assumptions in taking cases where the period of growth corresponds to the life of the property, but both Tables II and V are based on other assumptions. Besides this, it is worth bearing in mind that any property may be divided into a series of groups in which the investment term corresponds to the life term, and that each of these groups will follow a condition curve of its own. For a complex property, therefor, there would be a series of such curves which would give a resultant one. This resultant curve, however, would also vary over a considerable range. This is borne out by Curves VI and VIII of actual properties.

Since it will never be necessary to renew the entire property, some of the reserve necessary to return it to the 100 per cent condition may be dispensed with. It is not correct, however, to say that since the reserve will never be needed it should not be obtained. The stockholder has a right to expect that his capital be kept intact at 100 per cent. How then is the reserve to be handled? This is taken up as the third point.

There are three conditions which may be used as divisions for the consideration of the laying aside and use of depreciation reserve. These are:

1. Company growing at the great enough rate to permit the investment of all the reserve in extensions.
2. A company not growing at a great enough rate to permit the investment of all the reserve in extensions.
3. A company which is not growing.

Take the first case, where a company is growing at a great enough rate to permit the investment of all the reserve in extensions. It is clear that the annual charge for depreciation will, in some years be less, and in some years more, than the cost of renewals. In those years that the cost of renewals is less than the charge for depreciation, the difference may be invested in extensions, and in those years in which the cost of renewals is greater than the depreciation charge, it will be necessary to issue securities with the extensions made from reserve as a basis, using the money from the securities for the renewals. The securities, however, should not be issued to an amount greater than the depreciated value of the extensions. Wherever the depreciation reserve is invested in extensions, it is necessary to keep a careful record of property of this class. It is essential that separate accounts be kept for capital investment and reserve investment. The trouble in the past was that no attempt was made to keep them separate.

In the second case, where the company is not growing at a great enough rate to permit the investment in extensions of the difference between depreciation charge for the year and renewals for the year, and in the third case where the company has stopped growing, it will be necessary to keep the surplus of annual allowance over cost of renewal for certain years, in a liquid reserve fund, so as to be able to make up the deficiencies in other years. That some money must be so kept is now clear, for point one shows the wide fluctuations in per cent condition and in yearly renewals. How much must be so kept will be discussed under point four.

At present it is interesting to consider in what years the peak demands, requiring a security issue for the first case and a withdrawal of money from the liquid reserve in the second and third cases, will fall. In any complex property there are groups of things having different costs and different lives installed in the same and different years. If the cost is considered as amplitude, the lives as frequency, and the years as phase displacement it may readily be seen that as different waves come into step and pass out again, peaks and valleys will occur. In order to determine the variation in renewal charges it will be necessary to make tables and plot curves of the future renewals in each group. These curves will take the same general form as those in Curve VI, but will be for total replacement costs, instead of remaining service value as shown there. If tables are once compiled it is a simple matter to change them yearly as further extensions are made in the various groups. By following such a plan it will be easy to see whether or not adequate provision is being made for the handling of future extensions and to predict in what years it will be necessary to issue securities.

As described in the introduction, the second portion of point three is to show that by reinvesting depreciation reserve in extensions, the stockholders' capital is kept intact, yet the depreciated value of the property is the fair one for rate making purposes both from the point of view of the consumer and the stockholder.

Table V is for a property in which the depreciation reserve is invested in extensions. Let us consider the tenth year. Here the total expenditure on the property both from capital and reserve is $25,120, which has depreciated to $17,047. This latter sum plus $1953, which has been accumulated in the depreciation reserve during the past year and which as yet could not be reinvested, gives $19,000 the capital expenditure. Therefor, with the exception of the amount ($1953) accumulated in the reserve fund during the current year and not yet invested, the depreciated value of the property is equal to the capital investment. Omitting for the time being the question of allowing a return on the $1953 not reinvested, it is seen that allowing a return on the depreciated value of the property is practically equivalent to allowing a return on the original investment. The question of allowing a return on the amount held as liquid depreciation fund ($1953) in the above case will be considered under point five. This procedure described above, is therefor fair to the consumer, for he is paying a return on the value of the property in use, and it is fair to the stockholder for he is earning a return on his original capital.

The fourth point is to show that for a company which has stopped growing or for one which is growing at a rate not large enough to use all of the depreciation reserve for reinvestment in extensions, it will be necessary to have a continually varying amount in a liquid depreciation reserve fund and that this amount will fluctuate in a manner depending upon the company's growth.

Table V shows the condition for a property which has ceased to grow after ten years. At the end of the tenth year there are $1953 in the reserve. The sum laid aside annually for depreciation after that is $1884, yet owing to the fact that the company has grown faster at one time than at another, in some years there will be less than $1884 used for renewals and in some years more. The effect of this is to accumulate a fund over a certain period of years which is used over another period of years. Thus, starting with $1953 in the tenth year, the fund reaches a maximum of $10,149 in the twenty-fourth year; after which it decreases to $1953 again in the thirtieth year. This is graphically shown in Curve V. It is evident that since the $1953 will never be used as far as renewal purposes go, it may as well be returned to the stockholders. Since it is assumed that the company has stopped growing, the hypothesis precludes the possibility of using it for extensions and it should therefor be returned to the stockholders in the form of cash. It should be clearly understood by the stockholders that this is a return of capital and not a dividend payment.

Curve V is for the conditions assumed for this particular case. Any other manner of growth would give a different curve. In order to tell for any other property just what accumulation would take place and to determine how much, if anything, may be returned to the stockholders because it will never be used, it would be necessary to make a study similar to the one shown.

It is not very difficult to see that for a company which is growing, but at a rate too small to use all the reserve, that portion of the reserve which is not invested in extensions and betterments will bear the same relation to the renewals as the entire fund does in the case where the company is not growing at all. That is, there will be an accumulation curve for the liquid reserve which will be similar to the curve for a non-growing property.

In either case there will be a necessity for a liquid depreciation reserve for renewals and this reserve will vary from year to year. This fluctuation may be likened to the storage of energy in a flywheel. Just as there is no way to remove the energy from the flywheel except by stopping it, so there is no way of avoiding the fund as long as it is desired to make the renewals as they fall due. While the energy is stored in the flywheel it is of no direct use; yet it would be impossible to run the engine without a flywheel. The energy must be so stored to make it instantly available. The depreciation fund must also be stored to make it instantly available.

The fifth point is to show, that since such a liquid depreciation reserve may be necessary for a growing company and will be necessary for a company which has ceased to grow, that the same return should be allowed on such a reserve as on any other capital invested in the property, and that such return should be available for dividends, provided that the cost new, less depreciation is to be used as a basis for rate making.

Before trying to prove this point, the following decisions are given to show the stand taken in some cases in regard to this matter. The Nebraska State Railway Commission says in Re Application of the Lincoln Telephone and Telegraph Company, for authority to increase rates (A. T. & T. Co., Com. L.134 June 26, 1913, Nebraska State Railway Commission) "It will also be the policy of the Commission to expect of the corporation that it shall, so far as possible, use the depreciation funds . . . . in making extensions and betterment of the plant. Such part of the plant as is represented by the investment from the depreciation reserve shall be permitted to earn the same ratio of return as the stockholders' investment, but neither such reserve fund nor the earnings therefrom shall be available as dividends to stockholders, or for any other purposes than those set out."

In this decision the commission allows a return but it seems to consider the reserve as a sinking fund, the returns on which must be put into the fund. Further, it differentiates between investment from reserve and stockholders' investment as though the depreciation reserve were not also stockholders' investment.

In the Louisville and Nashville R. R. Co. v. Railroad Commission of Alabama the special master says (U. S. Circuit Co., Middle Dist. of Alabama. Report of Wm. A. Gunther, Special Master in Chancery, 1911) "The defendants further insist that interest should be allowed on the balance in the replacement account. It is a mistake to suppose that such a charge is proper."

Also in the case of the Louisiana R. R. Commission vs. Cumberland Telephone Co., (212 U. S. 425) the Court says: "That it was right to raise more money to pay for depreciation than was actually dispersed for the particular year there can be no doubt, for a reserve is necessary in any business of this kind, and so it might accumulate, but to raise more than money enough for the purpose and place a balance to the credit of capital upon which to pay dividends cannot be proper treatment."

There are two chief arguments against allowing a return on the depreciation fund. The first applies only to that portion which is not invested in extensions. It is to the effect that since the fund is lying idle, bringing no return, or is at best invested in bonds bringing a low return, that this is all the return to which it is entitled. The second argument applies either to the case where there is a liquid reserve or the reserve is invested in extensions. It is to the effect that since the money for the reserve is furnished by the consumer, he should not further be required to pay a return on it.

Taking the second argument first. The whole discussion hinges to a large extent on the question as to whether or not the stockholder may expect that his capital be kept intact at 100 per cent. How many men would go into a business of any kind if they could not make enough to replace their capital goods as they wore out and besides earn a return on their investment? That all businesses do not do this does not alter the fact that they expect to do so when they start. The recognition of depreciation and the allowance therefor is in itself an acknowledgment of the correctness of keeping the capital intact.

The capital which is wasting away is certainly the capital of the stockholder. He uses up his capital in the service of the consumer and the consumer replaces the capital so used. The consumer is making a just restitution. He is replacing something which originally belonged not to him but to some one else. Why then should the replaced capital have a different status from the original? It should not. The capital in a depreciation reserve fund should be treated the same as any other capital. It should be allowed the same return and for the same purposes.

Some argue that since the depreciation fund is lying idle (*i.e.* that portion not invested in extensions) or at best is invested where it brings only a low return, it is not entitled to more than it can earn. But is it lying idle? It has been shown that for any other than a growing company which can invest the entire reserve in extensions, there will necessarily be a continually varying amount in the liquid reserve. Besides this, even a growing company will have to carry from year to year some of the fund which it cannot reinvest at once. Is the depreciation reserve not just as necessary a part of the business as the working capital, of which there must always be a more or less fluctuating excess earning a low return, but which no one denies is entitled to the same rate of return as the capital actually invested in useful physical property? Is the liquid reserve, which is the stockholders' capital, not a guarantee to the consumer that the property will be maintained in first class operating condition and so give him the best of service? It may be said that he has a right to expect good service, but most people when not considering a public utility are willing to pay extra for good service. Thus, under competitive conditions a company which kept no reserve could give service at a lower rate than one which did, but it would be neither as good nor as reliable as that furnished by a company which kept a reserve. Would the public not be willing to pay for the greater reliability and better service?

No one questions the fairness of the proposition that the company be made to pay interest on deposits of consumers, yet in viewing that question the only consideration is that the consumer is deprived of the use of his money and should receive a recompense for it. The corporation's use of his money is not thought of for a moment in deciding whether or not such a charge is fair. To be sure, the company may devote it to a profitable use, but assuming that the company was not on a paying basis would that in any way alter its obligation to pay interest on the deposit? The stockholder is in much the same position as the consumer described above. He is deprived of the use of some of the money; but why should there be any further consideration of the justness of allowing him a return, regardless of what the corporation does with his money within legitimate limits, than there is in the case of the consumer? If the argument is to be that the funds are lying idle would it not be just as fair on the part of the corporation to say "Because the consumers' deposit will never have to be paid back in a lump sum, we will use them in our depreciation reserve and since it is lying idle we will have to pay no interest on the deposits"? What a howl would go up!

To bring out the point still more clearly, refer again to Table V. Suppose that an appraisal were made in the twenty-first year when the property was in a 39 per cent condition. It would be unfair to base rates on the $9783 which is the corresponding value of the property, when it is known that as the renewals are made the per cent condition will go up as high as 68. Under this scheme the rates would depend entirely upon the condition of the property in the year it was appraised and there can be no question as to the unfairness of such a proceeding. The rates should be based on the depreciated value of the property in any year plus the amount in the depreciation reserve, provided only that the sum is not greater than the original capital expenditure.

In conclusion it may be said (1) No matter how large a property is, it will not necessarily come to any fixed per cent condition nor anywhere near it. (2) The per cent condition of any property, the amount in the reserve fund, and the rise of the reserve fund depend upon the past, present, and future growth of the company, and that these conditions and their relations should be studied for any property whether a public utility or a private corporation. (3) Rates should be based upon the depreciated value of the property plus the amount in the depreciation reserve as long as the sum is not greater than one hundred per cent of the total capital investment.

DISCUSSION ON "THE EFFECT OF RECENT DECISIONS ON THE WORK OF INVENTORY AND APPRAISAL" (BETTS), "CONTINOUS INVENTORIES: THEIR PREPARATION AND VALUE" (CARVER,) "GROWTH AND DEPRECIATION" (LOEBENSTEIN), NEW YORK, NOVEMBER 10, 1916.

W. B. Jackson: I have been very much interested in this matter of detailed inventories and appraisals, and of the need of our electric properties and companies making the accounting of materials and plant coextensive, if I may put it that way, with the accounting of the money elements.

I believe that a detailed inventory and cost record of a public service property is valuable in giving to those in charge of the property a visualization of the property which they cannot obtain in any other way, both from the purely physical point of view and from the point of view of the spread of the cost over the property. Also it gives an exceptionally fine record by which to obtain the proper in and out charge in case of changes and improvements.

I believe that a careful record of ages should be kept of all property, for statistical purposes, but I do not believe that a so-called "depreciated value" or an estimated remaining useful life should be carried along as a part of the inventory and appraisal record, because it is likely to become seriously misleading, inasmuch as the estimated useful lives of the different parts of the property change as the months go by, almost as the days go by, and as they change, so change the estimated depreciated values.

The Wells Power Company, which is now operated by the Milwaukee Electric Railway and Light Company, the operations of which were directed by my firm for many years, carries a fully detailed inventory and cost record of its property. The records are in full detail, and as changes are made they are entered upon change sheets in like detail with the inventory. The change sheets cover the period of a year, at the end of which period the inventory is readily brought to date. These records are considered highly valuable by the managers of the Wells Power Company and the Milwaukee Electric Railway and Light Company.

Mr. Loebenstein's paper is more than anything else a demonstration of the extremely uncertain features of so-called "accrued depreciation," and of the serious danger in making it an important factor in determining the value of a property. In his consideration, he has taken the simplest possible assumptions, which do not agree with practical experience, and draws therefrom direct conclusions. Even with this relatively simple and academic handling of the subject, it is easy to see the uncertainty of the results arrived at. He has divided the property into classes of units, each class being assigned a useful life, and they are treated as though they would actually behave as they are assumed to behave, but they will not do so. Take, for example, a plant having four small steam turbine generators, to which, for illustration we may assign twenty-five years' useful life. There is not the least chance that these units actually comply with our assumption. At the end of ten years two might be displaced by a larger or improved unit, and after a while one or two more, and so on.

Let us consider another quite different character of property, such as wood poles. It is possible that fifteen years' useful life may be assigned to them. The useful life of wood poles, *per se*, may vary from six years to twenty years, and the character of ground in which the poles are set may cause a variation of 100 per cent or more in a fairly large system. And so we might analyze each class of property.

Thus, when we superimpose the uncertainties and complications arising from the variables which are found in practise upon Mr. Loebenstein's complex but relatively simple computations, we have a result upon which one certainly cannot predicate values with any reasonable degree of confidence.

Let me state, however, before closing, that where there are no figures developed from actual operation, the best estimate of the amount of annual appropriation, over and above current maintenance and repairs, that is necessary for deferred maintenance and renewals, can be obtained by the use of methods in the general line of those outlined by Mr. Loebenstein, but such year by year estimates, which may and should be revised periodically, are very different from formally predicating the value of the property on figures dependent upon such calculations.

G. W. Whittemore: In the consideration of this subject it may be worth the few moments necessary briefly to recall the several meanings of the term "depreciation", as it is generally used.

In Webster's Dictionary the word depreciation is given two meanings, viz:

1st "The act or process of depreciating", that is, the lessening in value of one kind or another.

2nd "The condition of being depreciated", or of having suffered a loss in value.

An act or process may differ from a state or condition merely as a cause differs from its effect. Yet the two meanings in this case are so lacking in identity, and the methods of expressing or measuring them so far apart, that the distinctions to be made in the unqualified term depreciation must be kept clear.

In the practical problems involved in the management of public and other utility properties, and in the consideration of the former by regulatory bodies, both of these branches of the subject of depreciation have been dealt with under various designations. Among the more common of such designations are:

Anticipated Depreciation, Theoretical Depreciation, or the Expense of Depreciation:

To the act or process of depreciation, as mentioned above, corresponds the preceding terms which are frequently used to denote this first branch of the subject.

As the term "anticipated depreciation" indicates, it implies the recognition of the fact that as time goes on, all property, as a rule, loses value, or suffers a reduction in the total quantity of service of which it was initially capable. We are accustomed to refer to permanent improvements and fixed capital. Strictly speaking, no improvements are permanent and no capital is fixed. Such property is permanent or fixed only in a relative sense, and in comparison with other forms of property of shorter life. Ultimately, all property used by a company or an individual in his business, except, generally speaking, land itself, is destined to ultimate retirement. "Repairs may postpone but cannot prevent such an outcome."

From this point of view the locomotive used in hauling a train is property consumed in operation, just as much as is the coal burned by the locomotive. The element of time is the only difference in the two cases. The coal may last a few hours. The locomotive may last many years. Eventually, both disappear as elements of cost in the conduct of the business.

Anticipated depreciation, considered quantitatively, is therefore an attempt to forecast the amount or proportion of the reduction in its initial value that will disappear from a property while ownership is retained. In other words, what is to be the total loss suffered during the process of depreciating.

Whether such loss is taken as occurring uniformly or not is a subordinate question. In any event, the final effect is the same; viz., the full amount of the anticipated depreciation is lost or consumed in the conduct of the business.

Such predictions as to the proportionate amount of loss vary, of course, for each class of property. They are estimates, and must all necessarily be based upon the accumulated experience of the past, and upon forecasts of the effects, each in its proper proportion, of the various influences recognized as tending to reduce the useful life of the particular portions of property under consideration.

The point to be borne in mind, as differentiating this anticipated from the other forms of depreciation, is that it is an attempt to look into the future and evaluate what such future may have in store.

Quite frequently, the term theoretical depreciation has been used in the sense in which anticipated depreciation has just been employed. The use of this term theoretical, however, would seem to offer some chance for misapprehension. Oftentimes the word theoretical is employed to contrast what is possible, but not likely, with what is real and certain. There is no doubt, however, about the reality and inevitability of this anticipated or theoretical depreciation. The only uncertainty connected with the subject is just how long the limited (and not unlimited), period of usefulness of the particular property in mind will continue.

In place of the term anticipated or theoretical depreciation, when the reference is to the act or process of depreciating, the uniform system of accounts prescribed by the Interstate Commerce Commission for the use of the telephone and telegraph companies, employs the term, the "expense of depreciation." Therein these words are defined as follows:

(a) The losses suffered through lessening in value of the tangible property from wear and tear that are not covered in any prescribed account covering current repairs.

(b) Obsolescence or inadequacy resulting from age, physical change or supercession by reason of any inventions or discoveries, change in public demand or public requirements; and

(c) Losses suffered through destruction of property by extraordinary casualties.

The companies referred to are compelled to include in their operating expenses amounts deemed sufficient to cover the anticipated losses of the character above mentioned, and thereby create proper reserves to recoup themselves when such losses occur.

Otherwise expressed, the particular class of expenses comprehended under the term of "expense of depreciation" are those for major repairs, replacements, or retirements, which experience shows will have to take place in any given property over and above those current minor repairs which must constantly be met.

Sometimes, as a convenient method of indicating the present expectations as to the lasting qualities of any portion of a particular property, this expense of depreciation is associated with, or expressed in terms of anticipated life of such same property. Those, however, who adopt this view should, of course, make careful distinction between what can be regarded as the gross rate at which a property is depreciating, and what may be called its net rate of depreciation. Suppose, as has been done in the examples used in Mr. Loebenstein's paper, that the expense of depreciation is taken at 10 per cent per annum. This means that in the course of 10 years it is expected that 100 per cent of the first cost of the property will have been charged against it under the head of theoretical depreciation or expense of depreciation. Suppose, however, that the property in question, say a particular machine, is from time to time the subject of renewals or replacements of parts of the machine, resulting, let us assume, in drafts upon the reserve for depreciation, amounting, on an average to 5 per cent per annum of the first cost of the property. The actual, or net, average rate of depreciation for the property would therefore be 5 per cent, and the resulting anticipated life of such a property would become 20 years, and not 10 years.

Accrued Depreciation and *Structural Value*: Corresponding with the second branch of the definition above mentioned, viz., the state or condition of being depreciated, are the other terms generally used when reference is made to this branch of the general subject of depreciation; viz., the present depreciated condition or, as the accounting system mentioned above terms it, the "structural value" of a property. These terms take into account such accrued depreciation as may be determined upon as actually existing in any particular plant. As thus used, accrued depreciation is, therefore, an attempt to measure past effects, as anticipated depreciation is to forecast future ones. The former undertakes to state what shrinkage in value can, as a fact, be found in any property not new. The latter endeavors to predict the amount of loss that will still take place in any property and, to the extent that the same can be approximated, the period of time over which such losses will be spread.

Perhaps the distinction which it is important should be recognized between the act or process of depreciating, whether called anticipated or theoretical, or the expense of depreciation, and the state or condition of being depreciated, as covered by the existing accrued depreciation of any property, whether physical or functional, can best be obtained from the accounting point of view as shown in the prescribed system of accounts already mentioned. Therein it is clearly shown that:

(a) The expense of depreciation, or its equivalent terms, refers to the future; accrued depreciation to the past.

(b) The expense of depreciation is concerned with the operating expense accounts; accrued depreciation with the fixed capital accounts.

(c) The measure of the expense of depreciation is that best estimate, based upon experience, that can be made as to the rate at which it seems likely capital will be consumed in operations in the future; the measure of accrued depreciation the best estimate possible to make of what amount of such capital consumption has, as recognizable facts, already occurred in the plant as it exists at the time of the inquiry.

(d) The time to which such expense of depreciation is to apply is the remaining life of the physical property; accrued depreciation to its expired life. During each such year that the property, or any portion thereof, will continue in use, the effort is to assess the company's earnings, in the form of an expense of depreciation, such uniform amount as will distribute, as nearly as may be, evenly throughout the life of the depreciating property, the burden of repairs (exclusive of current repairs for which provision is made under another account) and the costs of capital consumed in operations.

Both branches of the subject of depreciation into which it has been above divided are involved in appraisals and in rate investigations before commissions and courts.

One of the questions asked by commissions about any property whose fair value they may be trying to determine is this— "What is the reproduction cost, new, of such property?" Such question being assumed to have been satisfactorily answered, the commission can then be regarded as saying something like this. "We have now been told what the property would cost if created at this general time, and if it were all new. As a matter of fact, we know it is not all new. Let us remove this limitation as to newness. Now advise us as to how much less valuable this property may be, from the standpoint of how much less quantity-of-service of a proper quality it may contain, than would be a property entirely new.

The difference between the two amounts, as understood, would be the accrued depreciation that could be said to reside in such property, and which question was raised in the Idaho case referred to by Dr. Betts in his paper.

Besides wishing to ascertain the accrued depreciation in any particular property, the courts and commissions are also interested in those portions of the company's expenses which it may be charging against earnings under the heading of the expenses of depreciation, or the utility's estimate of the average rate at which the process of depreciating is in progress in the different parts of the utility's property.

To give this information to the regulatory bodies, special accounts have been set up under the prescribed accounting system. These show the results of any schedule of estimated rates of depreciation expenses adopted by the utility. They indicate, likewise, the drafts or charges being made from time to time against the reserve for depreciation resulting from such expense of depreciation charges.

Examinations of these accounts made by the regulatory body, or of the annual or other reports in which they are embodied, will indicate the rate at which such reserves may be accumulating, or, on the other hand, failing to accumulate. They also show the extent to which the appropriations for depreciation expense may have actually been meeting the particular burdens of major repairs, replacements or retirements of property which they are designed to cover, as indicated by the charges which may have been made against the depreciation reserve.

In Mr. Loebenstein's tables and curves both phases of depreciation as above indicated are taken into account, the expense of depreciation being equivalent to what Mr. Loebenstein refers to as "increments to the depreciation fund," while the present depreciated value or structural value corresponds to the per cent condition referred to in the same tables.

In determining what may be a proper expense for depreciation and, consequently, what may be the net rate at which a property is estimated as progressing toward a depreciated condition, a number of important factors must be taken into account. One of these factors is the element of growth. In some of the simpler cases, those in which this factor is the only one at work, the curves and tables shown by Mr. Loebenstein are intended to indicate what the results of a uniform expense of depreciation applied to a growing property would be upon the reserve for depreciation and the computed present condition of such property. For cases such as this the element of growth is shown to have a marked effect.

Generally speaking, it is believed that the influence of growth on the problems of depreciation is often not taken into sufficient account. Any property, particularly one of the composite character usually met with in actual cases, and one which is the subject of considerable and frequent additions of new elements, obviously will maintain a condition nearer newness than would a property not receiving such additions; so that, with respect to the depreciated condition of a property, either as to a particular time or as an average condition for any period, growth must be taken into account.

But, furthermore, if any attempt to test the reserve for depreciation as a ratio of the total plant in existence at the present time be adopted, the element of growth must here also be given its due weight. The amount in any reserve of depreciation is the result of the schedule of rates for the expense of depreciation which may have previously been in effect, and which rates have been applied to property previously in existence. Any drafts or charges which have been made against such reserves have, as a general proposition, been on account of property old enough to have reached a condition where major repairs, replacements, renewals, etc. have become necessary. Properly, therefore, the amount in such reserves should be related, as a ratio, only to that property which was in existence when such reserve was being accumulated. To refer such a reserve, so accumulated, to an entire property which might, perhaps, include recent additions, would result in a lower percentage of reserve to any plant than would have been the case if the ratio had been obtained before the additions referred to had been made. In other words, unless the element of growth be taken into a proper account, any comparison of reserve for accrued depreciation to the total present property, or any comparison of the effects of any particular schedule of depreciation expense rates to charges being made to the reserve for realized depreciation to cover concurrent major repairs, replacements, retirements, etc. may lead one into serious error.

Other elements beside growth have their effect upon depreciation in one of its phases or the other, and, as such, should be given their proper weight. Among such other influences might be mentioned any tendency which may be present to substitute the longer lived elements of a plant for the shorter lived ones now in place; another one might be improvements in design or engineering which would permit of necessary growth or enlargements without as extensive removals of previously existing plant as had before been necessary. Other influences might also be mentioned which would have their effect, either upon the expense of depreciation, or upon the accrued depreciation at any time in a property.

The value and purpose of computations such as Mr. Loebenstein has made are to be found, of course, in their demonstration of the effects that such elements can have in supposed cases.

In all instances, however, in which they enter they have some effect. And such elements have their effect even in those instances, not mathematically to be analyzed, where the actual property may, as in cases in mind, consist of 30 or more subdivisions, each of which relates to a different kind of property, each, subject to its own rate of growth or replacement, large or small, which growth or replacement may be quite irregular one year as against another; and which property subdivisions may be considered to have expectations of life ranging all the way from land, which is supposed to have no life limit, or vitrified clay conduit, whose life is indefinite, to other portions of the property which may require renewals every five or six years.

With respect to the relation of accrued depreciation to the base upon which to allow a fair distributable rate of return: as understood, Mr. Loebenstein regards as unfair for such purpose any base obtained through the deduction of any reserve for depreciation from the depreciated value of the property. Probably few, if any, will dissent from this view.

If the reserve for depreciation be deducted from anything, it would be nearer correct to subtract it from the undepreciated, instead of from the depreciated value of any property, whenever the problem under determination be the proper base upon which to allow a fair distributable rate of return.

And even in this case, such deduction of the reserve from the full 100 per cent value of the property, new, would not be based upon any consideration of depreciation, as such. Rather would it be founded upon the recognition of a divided equitable ownership in any property owing its existence, in part, to any depreciation reserve derived from the rate payers, and which reserve had been set up, specifically as such, in the company's accounts.

For the reserve for accrued depreciation, under the prescribed accounting system above referred to, can be regarded as amounts still standing to the credit of the rate payers, and representing specific provision by them for losses estimated as currently accruing in the property while they had been enjoying service from it. In time, such credited amounts will assist in covering future major repairs, replacements, or ultimate requirements of such property. Meantime, it is being held by the company, in some asset form or another, and offset by a special liability account showing the amount of such special assets, as a part of the total assets in the company's possession, until such major repairs, replacements, or retirements become necessary or economically justifiable.

Until the amounts in such reserve are actually absorbed for the purposes for which they had been collected from the consumers, it would seem correct to regard the equitable, although not the legal, title to the portion of the assets, in dollars, representing such amounts, as residing in the rate payers.

As thus viewed, therefore, if from the total assets held by the company, taken at 100 per cent of their full value, there be deducted that portion of the assets, also taken at 100 per cent of their value, new, owing their existence to the reserve for accrued depreciation as it may then stand in the accounts, the remaining assets would represent those held by the company, free from any such equitable claim of the creators of the accrued depreciation reserve.

Whether any further deductions should be made from a base derived as in the preceding, in the case of the utility which, in the past, had enjoyed earnings sufficiently ample to make full provision for any reserve for depreciation up to the amount of the real existing accrued depreciation in its property, but which had failed so to do; or whether, on the other hand, as items perhaps in its "going value", any addition to such base should be made in the case of the company which had made provisions to its reserve for depreciation, but had been compelled to do so in the face of inadequate distributions in the past to its owners, would seem to be separate questions—along with others which could be raised in this connection—for separate determination.

David B. Rushmore: There is one point concerned with depreciation which I have never heard mentioned in any discussion, and which I believe has not been taken in consideration by commissions or engineers in determining the proper figure for depreciation. Depreciation is an attempt—and it may be a very unwise attempt—to guess what the future has in store. An attempt is being made to keep the value of the capital invested intact by trying to guess just what the future will be.

When we are thinking of value, what are we thinking of? We say that the capital must remain the same, but value, as it really exists, exists only as regards the necessities of life, and the point which I have never seen considered, and on which I would like very much to hear an expression of opinion is why should not the factor of gold depreciation be considered in connection with the subject of the depreciation of property?

In the period of fifteen years from 1900 to 1915 gold depreciated on the average 3½ per cent a year, and the man who had his money in the savings bank, that was paying that much interest, was just keeping even in his position, while in the case of a man who owned bonds which paid interest of 3½ per cent, as some of them do, approximately, he was not getting ahead at all. Now, we are for the present moment existing under very abnormal conditions of economics, of finance, of trade, and apparently we are going to return to the same condition of gold depreciation. Therefore, why should not the permanent value of the property be measured in the value of the commodities which make up the necessities of life, and not in something which represents a medium of exchange or something which represents an artificial value, and which is not in itself fixed.

Edward J. Cheney: As Dr. Betts has very well said, it is necessary for us to abide by the decisions of the courts. It is also entirely proper that we should respect those decisions. I think, however, that the courts themselves are quite willing to be educated along the lines of these questions, which, because of their newness and complexity, are very perplexing to the judges. We should not be bound too rigidly by decisions with which we do not agree, but we should by just such meetings as this, endeavor to clarify the situation and enunciate proper principles. No one, I think, is so well qualified to put the matter in proper shape as engineers, who deal with the physical property and with actual operating conditions.

It is true that a great deal of stress has been laid on reproduction costs in valuation and rate cases of one sort and another, but that has doubtless often come about because in such cases accurate records of the investment cost were not available. I believe that when, as will in the near future be the case, records are available which show exactly what was spent for the property; and assuming that the investment was honest, prudent and timely; the money actually put in by the investors will be the proper basis for estimating a return in rate cases; and if so, it certainly will be the proper basis in purchase and sale cases.

It is a little bit off the subject, but I want to take this opportunity to register my emphatic protest against the use of two terms which are very commonly employed in connection with this subject. One is "going concern value". It is entirely misleading. I do not question at all the justice of including something for those items which are ordinarily included in the term, but the term itself is wrong. A public utility has no right to earn a return on an indefinite "going concern value" any more than it has a right to earn a return on what some have maintained was the franchise value. On the cost of establishing the business, on inadequate returns in the early stages, and on similar items, it has a right to expect a return, but let us call them what they are. The expression "cost of establishing the business" is more nearly correct, in my opinion, than anything else, and seems much preferable to "going concern value".

The other term which I object to is "contractors' profit". How many estimates we see with a percentage tacked on for "contractors' profit"! I maintain there is no such thing. The percentage a contractor gets, over and above labor and material cost, is to pay his overhead expenses and to pay him for his own services. He makes no profit. He may, it is true, make money on one job, but on another he will lose, and in the long run he gets only enough to keep him in business, and the percentage is not a profit but an item of expense. "Overhead expenses of construction" more nearly describes that item.

Relative to depreciation, public utility companies invariably expect that, in fixing rates, there be included in operating expenses the amount of estimated current and accruing depreciation. At the same time, they often, doubtlessly honestly, ask for a return on the full original cost of the property. If you lend me $1,000, you have a right to the interest on that money, but as soon as I pay back part of the principal the amount of interest is correspondingly reduced. Accrued depreciation, charged to operating expenses and paid in by the customers of the public utility company, is to that extent a return of the original capital.

William S. Franklin: I would like to point out, in connection with the question raised by Mr. Rushmore, that the influence of depreciated money or gold on the values of properties is taken account of in what is called "cost of reconstruction." The fact that gold does depreciate is an added reason for placing greater emphasis on cost of reproduction in estimating present values of a property.

The difficulty, however, is that the cost of reproduction includes another variable as well as the variation in the value of gold, namely, the variable which comes from improved methods and improved machinery, which may tend to lessen the value of the property as based on cost of reproduction, whereas the depreciation of gold alone would tend, if there were no advance in methods and machinery, to increase the money value of the property: If we could only devise some means for separating these two variables as they enter into the cost of reproduction, we could then take account of the two separate influences.

Philander Betts: In reference to the paper submitted by Mr. Carver, I want to emphasize two or three things that I have had in mind with regard to the value of keeping inventories and appraisals of a property, and of keeping them continuously up to date. The thought that has occurred to most people when you mention an inventory and appraisal is that the sole purpose has been to find out as of some given date the total amount of property in existence and its value at that time. That is only one of the reasons for making an inventory and appraisal of a property. The telephone companies for years have kept a continuous inventory, perhaps not in the same form that is usually employed in making up an appraisal, but it has been kept for operating reasons, so that the telephone company could know at any moment just where it had property, and how much it had, so that it could tell a prospective customer whether it could or could not furnish service of a certain character to a certain extent, and if it could not immediately furnish it, how soon it could furnish it.

Another reason for keeping an inventory, and along with that inventory the cost of the various portions of the plant as they are constructed, is in order to make the construction of the extensions more efficient. An analysis of construction costs is essential in the carrying on of any contractor's business. Why should not such an analysis be made of the construction costs of a public utility company? The keeping of such inventories, and accompanied with the inventory of the property the cost of the sections of the property, would lead to an analysis of the unit cost for those sections, which would show whether or not the extensions were constructed in the most efficient manner possible under all of the circumstances. Such an analysis might lead to better methods of doing the work. It might lead to doing the work at different times during the year, or, instead of doing it in certain piecemeal methods, without knowing just how much would be done, it might lead to doing it in a more systematic way.

In this connection I will call attention to what the telephone companies in the East do. Estimates are made up as to the probable growth in different directions—the probable number of new customers taken on—and estimates are also made as to where these customers will probably be located, and as to what property will probably be necessary. Orders are then entered for certain amounts of material a considerable time in advance. The total number of poles which are estimated to be used will probably be used without much change in the size and height of those poles. It may be that some changes will have to be made in the orders given for certain sizes and lengths of cables, but with a proper study based upon the running inventory, and the accompanying cost sheets, a company can certainly construct the additions to its plant in a more economical manner than is very often the case.

I want to answer some questions with regard to some of the points in my paper. I have referred to the fact that in several cases the courts have laid down the rule that what the company is entitled to earn a return upon, was the value of that which they devoted to the public use, and that this might entail deductions for property not at present in the use of the public. When I spoke of that I did not mean deductions for that portion of the property which was properly held in reserve. Every company that pretends to give continuous service must have property in addition to that demanded by the peak load in order to insure continuity of service. If companies are to take on customers from day to day, there must be some property created at least some little time in advance of its immediate use, so that there must be some reserve in the plant to accommodate these customers who come along every day. There must be some reserve in plant to safeguard against interruptions in service due to breakdowns of portions of the plant. They are every day occurrences, and must be guarded against, and the provision of a certain amount of spare plant is the usual and ordinary precaution.

I have in mind a definite case. In the southern part of New Jersey, there is a very large gas company situated about forty miles from Camden. Some years ago a project was evolved for the construction of a tunnel under the Delaware River from Philadelphia to Camden. The project was an ambitious one, some property was purchased and attempts made to float the scheme. Without going into the history of the case, suffice it to say that the scheme has never been carried through, but while the scheme was being thought of, a group of enterprising people went down into the lower part of New Jersey and formed eleven small gas companies in the towns and villages served by the railroads which would probably connect with the proposed tunnel. These eleven gas companies were later consolidated into one gas company, with a large central plant, which was built at a central point, and gas has been delivered for a number of years from that central point. In the design of that plant, care was taken to see that there was capacity for several times as many people as are found in the territory at the present time, with a view to all those who might have been found in that territory today, if that tunnel project had gone through.

Now, I submit this question, and I will leave it to you to answer it—would it be fair today to say that the people now served with gas in that territory should be charged rates that would give an adequate return on the value of the plant which was constructed and designed for several times as many people as are now making use of it? In all probability, if the promoters of the scheme had thought that the tunnel was not going through this gas company would never have been formed.

The point of it all is this: That a company, before it obtains a proper number of customers, is in such a developmental stage that it is impracticable to collect charges based upon a schedule of rates that would return a profit when the company is very small. The large gas company, to which I have referred, is in just that position. It must build its business up to a point where it will fit the plant which it has, before it can say to the customer that the rates must furnish a return on all its investment.

There is one thing which should be referred to in this discussion, and that is as to the power of the courts. The power of the courts seems to be misunderstood by some, in this way: courts have never had and do not now have the power to fix rates. The courts have the power to prevent confiscation, and to prevent, from the other standpoint, the collection of unreasonable rates. Probably all of the cases which have gone to the Supreme Court of the United States have gone there because the company contended that its property was being confiscated, and when the courts have held, as they have in some of the cases, that such returns as 3.5 and 4 per cent were not a sufficient basis for throwing the case out of court and declaring the rates improper, these decisions were based, not on the idea that such rates of return were adequate, in any sense, but that they were not confiscatory. That is all these decisions have ever said. The court can also determine whether the customers themselves are being asked to pay excessive rates.

In one of the cases before the New Jersey Commission, both the company, from its viewpoint, and the customers affected, from their viewpoint, appealed the case to the upper court. Why? Because the company, feeling that the rate was too low, contended that it amounted to a confiscation of its property.

The customers affected, on the other hand, appealed to the court, saying that the rates fixed by the commission were too high, and and involved collecting from them exorbitant charges. In that case the court did not pass on the facts, it determined that the facts had been passed on by the Commission, and the lower court decided it was neither confiscation, considered from the one direction, and did not say it was charging an exorbitant rate, considered from the other direction.

Harry E. Carver: In reference to the point Mr. Jackson brought up about the accrued depreciation on each item, you will notice that Forms 1 and 3, which constitute the Continuous Inventory Records, did not provide for the computation of the accrued depreciation on each item. They do, however provide space for recording data from which the accrued depreciation may be computed at any time it is desired. Hence, if it should seem advisable at any time to compute depreciation upon a different basis than that upon which it was previously estimated, the continuous inventory record would not be changed or altered in any way.

In connection with this subject some of you may have read the paper on "Continuous Inventories", which was presented at the last meeting of the American Electric Railway Association, held in Atlantic City, in which forms were worked out for each item year by year. I believe that these forms were made up in this manner because the taxing officials in New York State, and perhaps in some other states, require reports each year, in which information must be given as to both cost and the present value of property in considerable detail. If the depreciation is to be computed each year it seems that practically double work would be required in keeping the inventory records, because for every item of property there will have to be an entry made every year on the continuous record; whereas, if a summary only is made every year, the calculation as to the depreciation could probably be made covering a group of items and thus the amount of work would be greatly diminished. For that reason, and because of the great amount of estimating necessary in figuring depreciation, it seems to me it would hardly be advisable to attempt to make any depreciated values a part of the continuous inventories record.

W. R. McCann (by letter): It is to be inferred from a careful reading of Mr. Betts' paper, that the author submits the holdings of the courts to sanction *only* a reproduction method of valuing public-utility property, to the utter exclusion of all other methods. It is the belief of the writer that the correctness of such a deduction is to be challenged. In support of a contrary view, it may be well to examine one or two typical court decisions which apparently *may* be construed in accordance with the author's interpretation.

In the aforesaid paper, a pioneer case (*Smyth vs. Ames*) is cited to show that, in addition to the reproduction method, fair and reasonable rates should be fixed only after there have been ascertained the original cost of construction, the amount expended in permanent improvements, the amount and market value of its bonds and stock, the present as compared with the original cost of construction, the probable earning capacity of the property under particular rates, the sum required to meet operating expenses, and other matters. Certainly the case of *Smyth vs. Ames* does not support the exclusion of other evidence of value, in favor of a reproduction method as the sole and only correct theory.

The basis of the claims that the courts favor a reproduction theory is found in the language of certain judicial opinions—in language which is constructed to mean differently from what is actually stated. For instance, in *Des Moines Water Company, vs. City of Des Moines*, the court says:

> "The question is not what it (the plant) cost, although such evidence is admissible as having a bearing. The question is not what the plant some day may be worth, although evidence with reference thereto may be considered as having a bearing. The question is: What is the value of the plant today?"
>
> (192 *Fed.* 193, 196)

From such language it is argued that the value of the plant must be the reproduction value and that the words—"the question is not what it (the plant) cost", mean that an original-cost valuation is to be given no weight. There is a vast difference, however, between the price which has been paid *in toto* for a plant ("what the plant cost", to use the court's language) and a properly prepared original-cost valuation. A correct original-cost valuation has its basis in the same inventory as does the reproduction valuation; but, instead of present-day prices (or five-year average prices) being used in the appraisal, the actual cost prices are used for both labor and material, or, in the absence of records of the actual original costs of items of material and labor, the cost is estimated by a competent appraiser as of the time when the equipment was installed and under the precise conditions of its installation.

Likewise, in *Cumberland Telephone and Telegraph Company vs. City of Louisville*, the court said:

> "It would seem clear from the decisions that the most material question in such cases is that the *reasonable value* of the property 'at the time it is being used for the public', that is to say, the *time at which the question arises*—it being upon the reasonable valuation at that time that the company is entitled to earn a fair return * * * * The value of a plant may depend upon good fortune, upon good management, or upon fortuitous circumstances, but in every event the reasonable value of the property '*at the time it is used for the public*' is the value we are to ascertain for the purposes of this controversy."
>
> (187 *Fed.* 637, 642)

From the language "value of the property at the time it is used for the public" and from the similar language of other court decisions, it is again argued that the reproduction method must be used exclusively. It seems to have escaped the notice of the reproduction advocates that the language of the courts may well be interpreted to mean "the reasonable *depreciated* value of the *used and useful* property at the time it is used for the public".

Many courts have sanctioned and justified the reproduction theory because it is generally assumed that precise original cost ordinarily is difficult to secure. Usually the record before a court of review has little tangible evidence relating to a properly prepared original-cost valuation. The record may confuse the investment, the stocks and bonds, or a purchase price with the original cost of the various items embraced in the inventory. Before construing the language of a court which is reviewing a record taken in a trial court, it is well to ascertain first what that record contains on the subject of original cost.

Of a proper original-cost valuation, Ex-chairman Halford Erickson of the Railroad Commission of Wisconsin stated in a paper presented before the Conference on Valuation, held under the auspices of the Utilities Bureau, in Philadelphia, a year ago:

> "When the original cost of the existing property is desired it can be computed upon the same inventory as that used in determing the cost of reproduction and upon prices which cover the period when the property involved was put into the plant. Such price lists may be had partly from the records of the plant and partly from other sources. In this way the original cost of the existing property can be had with even greater accuracy than the cost of reproduction."
>
> (*The Utilities Magazine, Vol.* 1, *No.* 3, 113)

It is interesting to note that Chairman Erickson, after years of experience and participation in rate-making procedures, volunteers the opinion that even in the absence of books and records, "original cost of existing property can be had with even greater accuracy than the cost of reproduction."

Despite the many citations from court decisions favorable to some reproduction method of valuing utility property, it is noteworthy that no authority of standing is to be quoted to show that an estimate of the cost of reproducing the property (with or without deduction for accrued depreciation) is the sole and only guide to a reasonable and adequate valuation of a utility property for rate-making purposes. On the contrary, the inconsistencies of the reproduction method have been discussed time and again; it is only recently that the Supreme Court of the United States, in the *Des Moines Gas Case*, repudiated the reproduction method when applied to what, in valuation work, is commonly termed "undisturbed paving". The general unstableness of the reproduction-new theory was realized and understood by prominent proponents of the Federal Valuation Act. Senators Bristow of Kansas and LaFollette of Wisconsin, on February 24, 1913, participated in the following colloquy on the floor of the United States Senate:

Mr. Bristow:

"There is one point I wanted to bring out with regard to that feature of the bill that requires the Commission to ascertain the cost of production new. Such a finding, in my opinion, is not of any great value, so far as the rate making is concerned. It is a vacillating quantity; it does not represent in any sense the investment of the company in the construction of the road. To illustrate: In the suit that was pending, the estimated cost of the reproduction of the Northern Pacific Railroad was involved. I am informed the same engineer reported in 1907 and in 1909 as to the cost of the reproduction new, and the value fixed in 1909 was one hundred and eighty-five million dollars more than the same engineer fixed the value of reproduction new in 1907."

Mr. LaFollette (in part):

"Let me say to the Senator on this question that the Supreme Court of the United States has listed that as one of the values to be considered, and it has not yet by any express declaration eliminated it as a value to be ignored. So it seemed to the committee that we ought to give it, its place here. I will, however, say to the Senator that I am confident that the views of all the advanced commissions of the country that are doing this valuation work are that there should be very inconsiderable weight given to reproduction new."

(*Congressional Record*, 3801.)

The reproduction method of valuing property is relied upon by utilities mainly because it automatically takes care of the appreciation which has occurred during recent years in the cost-new of nearly all items of equipment and in all classes of labor. Land, in particular, falls into this classification, and a court of authority has ruled that the real property of a utility should be valued at its present-day market value, and not at its original cost plus the cost of improvements. Under the rulings of the courts, it may be argued that, even though a utility may steal equipment without being apprehended and may convert that equipment into used and useful property in the service of the public, the stolen equipment must receive due recognition in a valuation and rate-making proceeding. Whether or not this view will prevail ultimately, under a continuance of state regulation, is somewhat a debatable question at the present time. A simple case will serve to illustrate the fallacy of too great weight given indiscriminately to appreciation in utility property. Assume that an electric plant, in a state where the laws provide for state regulation, costs $100,000, and assume further that the regulatory body of jurisdiction, after investigation, has fixed rates such as will yield full operating expenses plus five per cent per annum ($5,000) for accruing depreciation and seven per cent per annum ($7,000) for a *fair* rate-of-return. At the end of five years, provided no change is made in the electric property, the utility has accumulated $25,000 (plus earnings) in a depreciation fund, and each year has paid a full and adequate rate-of-return upon this investment. During these five years, if perchance the prices of labor and materials advance so that the estimated reproduction-cost-new according to expert appraisers would be $110,000, there has been an unearned increment, over and above a fair rate-of-return, amounting to $10,000 in the value of the property—equivalent to $2,000 per year, or two per cent annually on the original cost. In other words, a valuation made at the end of the said five years, resulting in revised rates being fixed on an estimated reproduction theory, capitalizes an unearned increment which automatically results in rendering a nine per cent rate-of-return throughout the entire first five-year period. What has the utility done or denied to itself in order to deserve this unearned increment? Is not the public entitled to participate in the appreciation of property, at least to the extent of not having the same capitalized against it, to be borne by the rate-payers of the future? Carrying the illustration still further then, let it be assumed that the estimated reproduction value sinks to $90,000 at the end of five years; then the reverse is true, and the utility each year is deprived of just earnings equivalent to two per cent of the cost of the property. Under such conditions, would it not be argued that this deprivation of earnings would constitute a confiscation of property?

Such illustrations are indicative of the public's vital interest in what is termed "appreciation". It is to be borne in mind that "depreciation", as applied in valuation work, in no manner is the opposite of appreciation". An original-cost valuation, if properly compiled, does not presume to inflict upon a utility the losses occasioned by decreases in prices of material and labor. An original-cost valuation, however, does presume to reflect the conditions under which the bargain between a utility and its consumers was consummated. Under an original-cost valuation, the public sustains all losses due to the falling off of prices, although it participates in gains only to the extent of not having an unearned increment capitalized against it. As stated before, the courts have not stated that reproduction-cost-new (or less depreciation) must be the criterion by which to judge the present value of utility property for rate-making purposes.

The Massachusetts Public Service Commission, in its recent decision rendered *In Re Bay State Street Railway Company* (August 31, 1916), squarely recognizes that appreciation in land as disclosed by a reproduction method of valuing the same is not to receive recognition in a determination of rates:

> "Considering this appreciation upon its own merits, car riders cannot fairly be expected to pay higher fares because land has increased in value, nor ought they to pay lower fares if it should decrease. If the company wishes to sell such property it is, of course, entitled to whatever profit it is able to make; but so long as land is employed in the street railway business it is dedicated to a public use and held subject to the conditions fairly attaching to such use. As the Commission has said in another connection (see House Document No. 1900 of the current year, pp. 88,89): 'While no fair-minded man will deny that those who put their money into public service by building railroads are entitled to the oppor-

tunity to earn a fair reward, that this reward is to be determined, so long as their property is devoted to public use, not by investment or by service rendered, but in large measure by the rapid expansion of real estate prices in the larger centers of population, is contrary to sound public policy. It would mean that communities would be penalized by their own growth, and would lose all advantage from the fact that their transportation facilities were created in due season under favorable economic conditions.' It should be added that, even if the doctrine of present worth were accepted, the figure to be used in rate making would clearly be present worth for street railway purposes. In this case no evidence whatever has been submitted that the land has increased in value for such purposes."

(10 *Rate Research*, *pp*. 120 121,)

It would seem, therefore, that engineers as a whole may well listen to the admonitions of the courts, instead of becoming partisan advocates of some theory. Such biased acts on the part of the profession are accountable for rebukes of a type such as was administered forcibly by the late Judge Smith McPherson of Iowa, who, it is claimed by some, made a grievous error in the Missouri Rate Case (168 *Fed*. 317) by apparently giving too great weight to the testimony relating to certain new theories advanced by experts. In one of his last opinions, this caustic Iowa judge called attention to the great danger of experts. Judge McPherson's life was largely behind him, and he had had more than his fair share of experience as a United States district judge in endeavoring to weigh the evidence of experts in various public-service cases, when he said in the Des Moines Gas Case (199 *Fed*. 205):

"Too often we have selfish, partisan, prejudiced, and unreliable experts engaged for weeks at a time at $100 or more and expenses per day, exaggerating their importance and making the successful party in fact a loser."

Frank Gill: If Mr. Loebenstein contends that the plant of a normally conducted undertaking does not eventually settle down to a definite per cent condition, I do not agree with him, but if he only means that there is not a similar fixed percentage condition for all undertakings, I think he is quite right.

Fig. 1 shows the amount necessary in the depreciation fund for three theoretical cases, each with the same equated life but with a different rate of continuous growth. This clearly shows that each rate of growth results eventually in a definite per cent condition.

In each case there are 10 classes of plants having lives varying from 6 to 29 years and if a greater number of classes had been used, curves would have reached a steady condition at an earlier period.

Other calculations show that the per cent condition depends on the equated life of the plant as well as upon the rate of growth.

In these cases the Sinking Fund Method (at 5 per cent per annum) has been used for reasons which I consider conclusive, but this is really an independent question.

I do not think that Mr. Loebenstein has made sufficient allowance for the fact that while a definite life can be assigned to one class of plant, the individual components of that class do not in practise need renewals at exactly the same time.

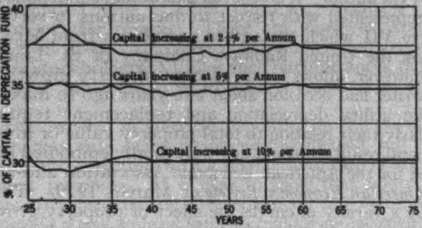


FIG. 1

I notice that in Mr. Loebenstein's calculations, he has allowed a full year's allowance for depreciation for the first year and if this is correct, it follows that the expenditure for the year took place on January 1st, and that the renewals would occur a full year sooner than shown.

L. R. Nash (by letter): It is surprising that a matter of so much importance as the effect of growth upon the average condition of physical property should have received so little attention in engineering literature. The paper on this subject by Mr. Loebenstein is very timely, particularly in view of the increasing attention to valuation studies in connection with rate regulation. The author's choice of public utilities to illustrate the points which he develops is to be commended because of the consistent growth and the predominance of valuation activity in this field.

It seems to me, however, that the illustrations which the author presents in tabular and curve form are not generally representative of average utility conditions. Most of these illustrations assume growth for a very limited period of years, after which the property remains stable. With this assumption, quite wide variations are found in renewal requirements and per cent condition. While the author points out that each of the cases assumed may be considered as one group of elements of a composite property, he still concludes that such a property would show a considerable variation from time to time in per cent condition.

Public utility history shows very few cases of property without sustained substantial growth. A few interurban railways and hydroelectric developments might be excepted, but the growth of the normal city requires continued expansion of its utilities. Even the case of the actual electric property, covering a period of one hundred years, which the author presents as an illustration, assumes that growth ceases after three years, the remaining ninety-seven years showing no expansion whatever. It is not surprising that under such an assumption the service value of the property shows a fluctuation between 37.5 per cent and 69 per cent as found by the author. It is believed that actual conditions are more nearly represented with respect to fluctuations in service value by Curve VII which the author reproduces from Mr. Allison's report on the United Railways Company of St. Louis. This curve, however, allows for no effect of property growth.

The writer had occasion about two years ago to make a study of public utility depreciation and replacement requirements, particularly their relation to total property value or investment. The general results of this study were finally embodied in a paper prepared for the American Economic Association and appearing in the *American Economic Review* of March, 1916. This paper shows by a variety of curves the effect of property growth, and gives formulas and tables for computing replacement requirements under certain assumed normal conditions. In connection with this study the writer had a table prepared showing the history of an assumed typical public utility for a period of one hundred years. The assumptions include growth at the rate of 10 per cent per year for the first twenty years, 7½ per cent per year for the next thirty years and 5 per cent for the remaining fifty years. The property was assumed to consist at all times of elements having useful lives uniformly distributed between ten and thirty years and an equal value of elements in each life group. A copy of that part of the table showing for each year the total investment, cost of replacement of discarded property and the relation between the two is presented as Table I. While this table does not directly show per cent condition, it is believed that uniformity in annual replacement requirements implies corresponding uniformity in per cent condition if, as assumed, all replacement requirements are given prompt and systematic attention. A study of the attached table shows a surprisingly close agreement among the ratios of replacement cost to total investment. There is, in fact, during the last twenty years of the period a variation of only about two per cent in the yearly percentages from their average. In earlier years there is, of course, less consistency because of changes in rate of growth and immaturity of the elements of the property. It is the writer's belief that the attached table represents fairly closely the normal condition of an urban utility, although the assumed uniformity in value of elements and regularity of life will not obtain in practise. This does not sustain the author's conclusions that no approximation to uniformity in per cent condition is to be expected even if growth continues. As the rate of growth increases, per cent condition will normally increase with full maintenance but, as the author states, a large liquid depreciation reserve is not necessary.

The author further comes to the conclusion that depreciated values should be used in determining equitable rates, basing this contention upon calculations which show that depreciated value and depreciation reserve are together equal to capital investment. If adequate depreciation reserves were always available, there would be no question of injustice to investors in using depreciated value, if a full return were available from an investment of the reserve. There are, however, state laws which prohibit distribution of income from invested depreciation reserves to stockholders. Under such circumstances the use of a depreciated value would deprive the investor of an adequate return.

The writer wishes to voice his opposition to the use of depreciated values in rate cases, recommending instead, full value or investment in connection with a sinking fund rate of accrual for replacement purposes. It is easy to show that under normal conditions the combination of a return on full value plus the comparatively small sinking fund accrual for replacements is approximately equal to a return on depreciated value together with the larger straight line accrual for replacements.

The depreciated value method involves several serious difficulties. The average utility does not earn an adequate replacement reserve in its early years, and with a reasonable hope of making up the deficiency in later more prosperous years when funds are actually needed, dividends are given early preference. The utility may fully expect to adequately provide for all the necessary upkeep of its property, but would be seriously embarrassed by an early rate proceeding which established a depreciated value before the supplementary replacement reserve was accumulated. Furthermore, in a rate case where the utility had carefully accumulated what in its judgment was a full depreciation reserve, it would probably be found that engineers of the supervising commission would find in their judgment, on examination of the property, a higher or lower depreciated value than that estimated by the utility. To the extent of the difference between the two estimates the patrons of the utility or the utility itself would be done an injustice in a rate proceeding. Such probable injustice is entirely avoided by using an undepreciated value with a sinking fund rate of accrual, which requires compounding of the annual contributions to the reserve to make up full ultimate replacement requirements. Utility and commission may disagree upon the useful life of physical property but such disagreement does not affect the investor's return, involving only the amount which patrons should contribute for the upkeep of the property. There is usually ample opportunity of adjusting and readjusting the annual accruals for replacements to meet actual requirements. If a commission finds that a utility has neglected to accumulate a suitable reserve, and at the same time has paid excessive dividends, the proper remedy, it is submitted, is to order a reduction in rate of dividends until the earlier excess has been offset rather than to permanently reduce the fair value of the property.

With the sinking fund method it is necessary to provide safe investment for the annual accruals with adequate return thereon. There is usually sufficient growth in public service properties so that they may invest their reserves in their own business, such investments being accounted for separately from property for which outside investors have furnished the funds. The requirements for a liquid reserve are not different from those under the straight line method. In the long run with approximately uniform replacements, about 60 per cent of the annual cost is provided from current contributions, the balance from income of the invested reserve which will normally accumulate during the early years of the business to approximately 40 per cent of the total investment.

The author assumes that if a utility stops growing and cannot use straight line replacement accruals for the temporary financing of extensions, such accruals might be returned to stockholders in cash, as a part return of capital and not as a dividend. It is believed that such a procedure is distinctly undesirable in the case of public utilities. Conditions might arise in which, without material growth the original property was allowed to seriously depreciate and a large proportion of its original cost be returned to the investors in addition to dividends. In case of unwise regulative restrictions, the investors might decide under such circumstances, that it would be expedient to salvage their property and discontinue the business rather than submit to further injustice. Such discontinuance of an established utility service would be very much against the public interest and its possibility should be avoided by restricting routine payments to investors, to interest and dividends only.

The writer finds it helpful to think of the public service problem as involving three distinct interested parties instead of the two parties ordinarily recognized in discussions, namely, the public and the investor. Between these two parties at interest the utility itself may be distinguished as a third party. The utility is by no means identical with the investor. It looks to the investor for funds as it looks to the public for patronage. It is no more subject to the command of one than to the other, unless it be that through regulating bodies the public has assumed a more dominant position. The utility should be looked upon as the custodian of property or an agent or trustee for both the public and the investor. As an agent it is an intermediary in all transactions; it receives the customers payments for services, disburses a part of them for expenses, taxes, etc., distributes a part to the investors who have furnished construction funds, and should retain a part for conservation of the property and for contingencies. The investor has no more right to demand a specific return from the utility for the use of his money than the public has to demand a specific kind of service. That the utility is or should be trustee of funds set aside for replacements to which the investor has no right is a point commonly overlooked

TABLE I

STUDY OF REPLACEMENT COSTS OF A TYPICAL UTILITY PROPERTY.

Initial property value $10,000. Is composed of twenty units of equal value. The first unit is discarded and replacement made at end of ten years, second unit at end of eleven years and third unit at end of twelve years, et cetera. New property is acquired at rate of 10 per cent for twenty years, 7.5 per cent for thirty years and 5 per cent for fifty years. Each yearly increase represents the addition of twenty new units and these units are discarded and replacements made after the tenth, eleventh, twelfth year, et cetera, in the same manner as the original twenty units.

Year	Value at beginning of each year	Increase during year	Cost of replacing discarded property	Ratio of replacements to value at end of each year
1	$ 10,000	$ 1,000	$ ..	..
2	11,000	1,100	..	..
3	12,100	1,210	..	..
4	13,310	1,331	..	..
5	14,641	1,464	..	..
6	16,105	1,610	..	..
7	17,715	1,771	..	..
8	19,486	1,949	..	..
9	21,435	2,143	..	..
10	23,578	2,358	500	1.93
11	25,936	2,594	550	1.93
12	28,530	2,853	605	1.93
13	31,383	3,138	665	1.93
14	34,521	3,452	732	1.93
15	37,973	3,797	805	1.93
16	41,770	4,177	885	1.93
17	45,947	4,595	974	1.93
18	50,542	5,054	1,071	1.93
19	55,596	5,560	1,178	1.93
20	61,156	6,116	1,795	2.67
21	67,272	5,045	1,474	2.08
22	72,317	5,424	2,121	2.73
23	77,741	5,831	1,832	2.19
24	83,572	6,268	2,516	2.80
25	89,840	6,738	2,266	2.34
26	96,578	7,243	2,993	2.88
27	103,821	7,787	2,792	2.50
28	111,608	8,371	3,571	2.97
29	119,979	8,998	3,429	2.66
30	128,977	9,673	4,271	3.08
31	138,650	10,399	3,615	2.42
32	149,049	11,179	4,386	2.74
33	160,228	12,017	4,728	2.74
34	172,245	12,918	5,097	2.75
35	185,163	13,887	4,995	2.51
36	199,050	14,929	6,344	2.96
37	213,979	16,048	5,884	2.56
38	230,027	17,252	6,828	2.76
39	247,279	18,546	7,362	2.77
40	265,825	19,937	8,440	2.95
41	285,762	21,432	8,029	2.61
42	307,194	23,040	9,640	2.92
43	330,234	24,768	9,316	2.62
44	355,002	26,625	11,019	2.89
45	381,627	28,622	11,293	2.75
46	410,249	30,769	12,153	2.76
47	441,018	33,076	12,496	2.63

TABLE I

STUDY OF REPLACEMENT COSTS OF A TYPICAL UTILITY PROPERTY.

(Continued.)

Year	Value at beginning of each year	Increase during year	Cost of replacing discarded property	Ratio of replacements to value at end of each year
48	474,094	35,557	14,922	2.92
49	509,651	38,224	14,495	2.64
50	547,875	41,091	16,564	2.81
51	588,966	29,448	17,240	2.79
52	618,414	30,921	19,108	2.94
53	649,335	32,467	19,555	2.87
54	681,802	34,090	22,007	3.08
55	715,892	35,795	23,177	3.08
56	751,687	37,584	25,494	3.23
57	789,271	39,464	26,849	3.24
58	828,735	41,437	28,946	3.32
59	870,172	43,509	30,639	3.35
60	913,681	45,684	34,931	3.64
61	959,365	47,968	34,784	3.45
62	1,007,333	50,367	36,699	3.47
63	1,057,700	52,885	39,066	3.52
64	1,110,585	55,529	41,233	3.54
65	1,116,114	58,306	43,372	3.54
66	1,224,420	61,221	46,192	3.59
67	1,285,641	64,282	47,702	3.53
68	1,349,923	67,496	50,822	3.58
69	1,417,419	70,871	53,415	3.50
70	1,488,290	74,414	57,315	3.67
71	1,562,704	78,135	58,152	3.54
72	1,640,839	82,042	62,713	3.64
73	1,722,881	86,144	63,779	3.52
74	1,809,025	90,451	67,180	3.54
75	1,899,476	94,974	70,869	3.55
76	1,994,450	99,722	74,043	3.54
77	2,094,172	104,709	77,066	3.51
78	2,198,881	109,944	81,482	3.53
79	2,308,825	115,441	83,935	3.46
80	2,424,266	121,213	89,712	3.53
81	2,545,479	127,274	92,312	3.45
82	2,672,753	133,638	97,208	3.46
83	2,806,391	140,320	102,142	3.47
84	2,946,711	147,336	109,251	3.53
85	3,094,047	154,702	113,345	3.49
86	3,248,749	162,437	119,282	3.49
87	3,411,186	170,559	125,027	3.49
88	3,581,745	179,087	132,616	3.53
89	3,760,832	188,042	138,420	3.51
90	3,948,874	197,444	146,930	3.54
91	4,146,318	207,316	152,658	3.59
92	4,353,634	217,682	161,182	3.54
93	4,571,316	228,566	168,004	3.50
94	4,799,882	239,994	177,283	3.52
95	5,039,876	251,994	186,168	3.52
96	5,291,870	264,593	196,510	3.54
97	5,556,463	277,823	205,021	3.51
98	5,834,286	291,714	216,618	3.54
99	6,126,000	306,300	226,128	3.52
100	6,432,000	321,615	237,830	3.52

and which, if given proper consideration, would very much simplify depreciation studies.

It should be clear from the author's paper that any full pro rata accrual for replacements results in a reserve which, in a growing property, is never used. It may be of interest to note, in connection with the history of an assumed utility shown in the accompanying table, that the annual replacement requirements of this utility could be taken care of by an accrual without interest accumulations, started after the end of ten years, at the rate of 3 per cent for the next forty years, 3.5 per cent for the following fifteen years and 3.69 per cent for the final thirty-five years. Such accruals, entirely absent from the first ten years, not only take care of all annual requirements, but accumulate an unused reserve which is always slightly greater than the current annual requirements.

F. C. Merriell (by letter): The matters placed in issue by the recent papers on appraisal and inventory seem to be merely a reopening of what has always been a fruitless inquiry. The general nature of the decisions of courts indicates clearly that practise and present needs have far outrun the enlightenment of the judiciary in this matter. The only factor contributing in any great degree to the solution of the problem, which comes from the courts, is a grudging recognition that value is the matter in question rather than cost, and that generally, items of value are more various and inclusive than items of cost.

For the use of courts, commissions, and the operators of property, an accurate inventory of property is a necessity and if it can be maintained continuous, it has the added advantage and no mean one, that all the force of the operator will be educated in the business of appraisal. This is a lack sadly felt at present and the use of most inventories is greatly limited because of it. A case in point is the inventory of a large utility, with which the writer was recently associated. The necessary field force was so unversed in the elements of value resident in such property that the inventory did not at all meet the requirement which necessitated it, and had to be supplemented with much special field work to make it adequate. It was in the first instance, unusually accurate and complete as to quantity, but the saving grace of well trained and exercised judgment was not always apparent in the first listing. A continuing education in this important branch of engineering, will quite materially assist to a better appreciation of how constituent parts of property account may best be identified in inventories, and more important still, it ought to increase the knowledge of how best to apply, and when most economically to expend renewal and maintenance funds.

In his paper Mr. Loebenstein sets up a number of paradoxical cases, because he makes his appeal only on the basis of physical cost and not upon the basis of value. In order, if possible, to join the issue let an extreme case be cited.

A pole line has been built through a desolate country and provides service between the communities at its ends. It is no matter for consideration whether the property shall have been a wise investment or not, but for a specific case it may be assumed that the service is adequate and that the projectors are making a profit. Every part of the property has however, suffered a lessening from its merchant price, by reason of the handling incident to erection, and by its removal from the regular channel of trade to its present location. Thus early it begins to appear that the merchant price has ceased to be a criterion of its value, even as property merely, and the charges which have been added to the merchant cost, while necessary for the specific service are in a very real way penalties against that cost or price when all the factors going to make its condition purely as property, are considered.

The country being desolate and uninhabited, it may very well be, indeed, that the property has no commercial worth whatever, no matter what its physical state may be. Many such lines exist today which cannot be dismantled, should such a thing be contemplated. The poles are not numerous enough to pay to gather them for firewood, at the expense of the labor per pole involved. The more durable units of property cannot be sold for the cost of their collection. Irrespective of the physical cost or condition therefore, this property is quite worthless as such and neither additions to it nor extensions nor enlargements of it will in any case increase its worth as property, in its location. In this case it appears that the criterion of the value of the property is not its worth as so many units of various physical things, but in its opportunity as a conception and its adequacy as the realization or embodiment of that conception.

Therefore the physical cost is an element only in so far as it enables the entrepreneur to demonstrate that he has done an adequate thing economically and that no penalty ought to be levied against him for the cost he has so far incurred because he is supplying an obvious need; and further that this physical cost together with all the other things he has done, appraised at their proper price, which make the property a utile and reliable public institution, are to be included in determining its value.

It has been attempted to show that the physical cost or condition is really a minor factor in arriving at value, and if that inference can be drawn from the extreme case cited, what follows may seem logical. The physical cost having been admitted as one, and not the only, element of value, and specific condition being a mere derivative of the course of all things physical and the fact of their existence, a further assumption is taken. If it was worth for the original purpose of the undertaking, all it cost to place the various units of property in their present position and use, how can it be said from that time each such unit began inexorably and without qualification to become of less worth. The fact which is well known and a stubborn one, that nearly every kind of property passes through a long period after its first utilization, when the value of its service does not appreciably lessen, is vital here, and points to the conclusion that the character of its use and the length of time it will continue to render satisfactory service, are the real criteria of its value and that physical appearance or condition is of little moment, except as it is the visible evidence of care and forethought, (or the lack of these) in maintaining the property.

The fact that renewal or replacement would be necessary did not in the first instance surprise the entrepreneur, for he accepted these things as one of the necessary risks or expenses of his business. He has never charged himself with the duty of creating a certain standard of appearance in his property to betoken a satisfactory condition, but has rather given his best perception to the effort to detect the first falling off from the highest standard of service, and has esteemed the deterioration of his property to be first betrayed by its failure to render that high type of service. He is not and never can be interested in an attempt to ascertain what percentage of condition as merchant property his plant has reached, but he is vitally interested if it appears that he must increase its facilities or replace some of its units to keep it doing what is required of it.

If he be called upon at any time to evaluate the property, it is generally agreed that he has a right in its physical condition, which might be even better expressed if it were said that he had a duty to make those changes and renewals which will serve to maintain the standard of its usefulness. If he has accumulated funds for all the charges in reasonable prospect, he ought not to be said to own less than he formerly did. If he sell his property he will expect to receive the full price of it, including the amount of his provision for the future or he will take the sum he has so set aside as a part of the purchase price and the purchaser will thereupon have to set up a similar fund in order properly to administer it. Current practise thus illustrates that the concept of depreciation cannot make its way against the logic of actuality. And the property, which, having no provision for proper renewals and needing them, is sold, suffers in price to exactly the degree in which it has been neglected, thus proving in too many cases that the protection of regulation has not at the present reached that bi-lateral efficiency which has always been so strongly urged for it.

The projector, when he undertakes the business has certain definite aims: on the one hand to supply such a commodity as will be acceptable to his public; on the other to gain as much as he may; and as a corollary of the latter he expects nothing else than that the business shall maintain all the necessary charges as well as the profit he desires, and that consensus of opinion called good practise, supports him in the idea that he ought, if he can, to make renewals and replacements in the ordinary sense from earnings, inasmuch as these are ordinary things, to be ordinarily met. If it is right therefore to take from earnings to make good these things, it is wrong to contend that the earnings so taken are a penalty against capital and reduce it by so much. If the provision is not made, the capital is indeed subject to reduction in the amount required for—what? To replace any fixed percentage of physical condition? By no means. To restore the service. If it were possible, there could be nothing more desirable than a uniform method, which could in fairness be applied, to assure that there was the proper intention on the part of the projector to continue his effort to give adequate service, which is the end really to be served by such provision, but experience demonstrates that uniformity is not in any very immediate prospect as a solution in this matter.

This view of the matter of so-called depreciation is not a new one, the writer having first formulated it to his own satisfaction in a private report some five years ago. As long as four years ago the receiver of a large utility defended and made good his defense of the attitude that he would not recognize any scheme of artificial penalization in lieu of his forethought and skill as a manager. A discussion of the whole matter from quite a similar viewpoint and with more attention to the mechanism of the scheme was published by Mr. C. E. Grunsky in Vol. LXXIX *Trans.* A. S. C. E. Finally it must be said that much of the difficulty of the whole matter at issue will be solved when it is recognized as a basis, that projectors, as corporations or the creators of corporations, are not willing to accept cheerfully any less fairness than any other component part of the public is willing to have.

J. Loebenstein: Referring to Mr. Nash's discussion, I call attention to the fact that when appraisals are made and estimates of requirements for future renewals desired, these estimates are made on the assumption that end of growth has been reached. Our predictions of what will be necessary in the futurer are based on what we know of the past. It will certainly be necessary to revise our estimates from time to time, but these revisions will in turn be based upon the past.

The Curve VII, which Mr. Nash notes, is based on the assumption that end of growth has been reached just as is Curve VIII.

In Mr. Merriell's discussion the statement is made: "If he sell his property he will expect to receive the full price of it, including the amount of his provision for the future or he will take the sum he has set aside as a part of the purchase price and the purchaser will thereupon have to set up a similar fund in order properly to administer it."

In my paper I tried to show what factors should be considered and in what manner the funds above referred to should be gathered. This cannot be done without some projected basis of renewals, based on the physical cost which Mr. Merriell considers only a minor factor.

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CERAMICS IN RELATION TO THE DURABILITY OF PORCELAIN SUSPENSION INSULATORS

BY HARRIS J. RYAN

ABSTRACT OF PAPER

The fundamental requirements in satisfactory high-voltage line insulators are summarized and particular emphasis is placed upon the need for coordinated study of service durability. The effect of porosity upon durability is explained in detail and an appeal made for the establishment of a practical porosity elimination test.

The manufacture and structure of electrical porcelain is studied from the viewpoint of the ceramist, with many quotations and illustrations taken from the Transactions of the American Ceramic Society.

The author briefly states the conclusions at which he has arrived and gives a very complete list of references and notes.

DURABILITY is one of several fundamental requirements in a satisfactory high-voltage line insulator. These requiredents are:

1. Electrical Requirements.
   a. Electrical strength of dielectric.
   b. Refractoriness of dielectric.
   c. Design of electrical features.
2. Mechanical Requirements.
   a. Mechanical strength and toughness of dielectric.
   b. Design of mechanical and thermal features and their coordination with requisite electrical features.
3. Durability Requirement.
   Minimum attainable deterioration.
4. Cost Requirement.
   Best insulators that the art can produce at a minimum cost which the practise can afford.

The modern porcelain suspension insulator is generally accepted in the present state of the art as meeting the above requirements to the greatest extent. In respect to these requirements the service it renders is reasonably satisfactory except as to durability. Effort is now being made by manufacturers and engineers to produce and to accept only such high-voltage porcelain insulators as will not fail under ordinary conditions of use or non-use in ten years or more. As yet there is no assurance that this result has been accomplished. If the causes of the failure of insulators with time were fully understood, more effective work could be done to eliminate them. At present, after much effort in many quarters, these causes are known and understood only to a limited extent.

Hardly any of the requirements of an insulator stand alone and unrelated to the rest. Particularly is this true of durability. Most of the features and of the properties of the materials that constitute an insulator are related to its durability. It is not reasonable to expect, therefore, that decided improvement in the durability of the insulator can be made without a thorough going study by which full knowledge will be developed of all the facts for the materials and their forms that enter into the make-up of the insulator.

There are two distinct phases of durability:

1. Ability to endure sufficiently an adopted set of *acceptance tests*.
2. Ability to endure operating service conditions and the action of the elements during a reasonably long period of time, *i.e.*, ten years and upwards.

We may for the present call the former *acceptance durability* and the latter *service durability*.

Insulators must be bought and paid for largely through the results of acceptance tests. On account of the great length of time involved, few if any can be bought on the basis of an ultimate durability in service which years alone can determine. The present day suspension insulator was introduced nearly ten years ago and service durability results are now accumulating rapidly. It is generally conceded that the difference between acceptance and service durabilities is too great and must be reduced. The remedy is being sought for and applied through causes of failures in and out of service as related to the past and present states of the art. A large amount of coordinated effort of all concerned and able to take part is required to discover these causes. The study of the service durability of high-voltage insulators must have a number of well defined and not-to-be-forgotten *points of application* in order that the greatest advance in this durability may ultimately be attained; they are:

1. Insulators that have and have not failed in service.
2. Insulators that have deteriorated when not in service.
3. Laboratory treatments that will cause insulators to fail.

4. Factory materials, design and technique in relation to subsequent failure of insulators.

5. Laboratory science studies of everything that can be perceived about the materials, their form and assembly for insulators.

6. Coordination of all known knowledge that can have any possible bearing upon insulator durability.

Studies have to be made by factory and transmission engineers and by ceramists, geologists, chemists and physicists at all of these specified points of application. Everywhere the work amounts to little more than a beginning and much more remains to be done if the porcelain insulator is to be made thoroughly reliable in practise.

In a conference with Dr. J. C. Branner, a geologist with a wide knowledge of rock, clay and earth products, it was learned that high durability must not be expected of *porous* bodies even when they are constituted of porcelain. To retain the original integrity of clay products generally their vitrification must be carried far enough to make them virtually proof against the absorption of moisture. In witness thereof, he exhibited a porous clay product dish covered with an imperfect glaze. A student in biology for a comtemplated experiment had dissolved a salt in some water placed in this dish. Interest in the undertaking was then lost and the dish containing the solution was allowed to stand in the laboratory untouched for a number of weeks. In the meantime the solution entered quite generally into the pores of the porous dish body. Later as the water evaporated from the dish and from its porous body salt was deposited throughout the pores. The salt formed crystalline structures that developed excessive internal mechanical stresses throughout the dish. Complete ruin of the dish resulted, chiefly through the production of large and small spalls and cracks. As a structure, however, the dish had remained whole. In respect hereof materials in solution are divided into two classes:

1. Materials that expand when passing from the liquid to the solid state by freezing or by crystallizing from a saturated solution

2. Materials that do not expand in the same circumstances.[14]

The former materials only produce the mechanical injury in porous structures, though injury by electric conduction that each class of materials may cause, so long as any moisture remains in them, must ever be kept in mind.

Regarding the claim that ample vitrification of porcelain will make it brittle and mechanically unreliable, it was learned from the same authority that the way out of the difficulty should be to select materials that would have to be vitrified at higher temperatures resulting in a greater toughness of product. As evidence thereof the production of satisfactory paving brick in our country was referred to. This is accomplished by ample vitrification of materials so chosen and proportioned that high temperatures must be applied for the result. The enhanced durability of the brick is worth more than the increased cost of vitrifying at the higher temperatures.

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[14] For references see notes at end of paper.

It has long been known that porcelain for high-voltage line insulators affords no dependable service durability when made by the dry process and that a fair service durability for a large portion of the product is rendered when made by the wet process. In dry process porcelain the porosity can be reduced to one per cent only with difficulty,[1] whereas in a major portion of the high grade wet process porcelain the porosity is, by comparison, very low *i.e. one tenth* per cent or less.[2] Thus practical experience establishes the fact that the lowest degree of porosity that the art can be made to produce is a service durability requirement of the highest importance. Porous porcelain when waterlogged becomes virtually an electrolytic conductor and a failure as an insulator. Its failure to insulate would be less decisive if under the circumstances its temperature-resistivity coefficient were not negative in sign and so high in value. As soon as local heat is generated the whole current flowing through the porcelain body must inevitably be concentrated upon a route so narrow that intense heating occurs resulting in fusion or burning and the production of a conducting core.

Portland cement is generally used to attach the metal pins and caps to the porcelain insulator bodies. The details of cement curing are well known. First a saturated solution is formed of the new cement in the excess of water present. When the insulator body is porous such saturated solution is absorbed. Later all free water evaporates and the material in solution in the pores of the porcelain remains as crystals producing great mechanical stresses as already shown.

Insulators are carefully designed to minimize cracking of the porcelain body by thermal expansion stresses. With porcelain sufficiently porous to permit cement crystals to form within the body it would seem to be too much to expect of any design that no cracks would occur. The combination of mechanical stresses produced by the crystals and by differential thermal expansions must inevitably produce more cracks in the porcelain body than from these causes acting alone.

Porous porcelain in an insulator captures moisture in damp weather and liberates it in dry weather. Each weather cycle will deposit, however minute, a certain quota of soluble salts. Thus eventually salt will have accumulated in the porcelain body to such an extent that it must fail as a dielectric due to cracks in dry weather increased by sudden temperature changes or by electrolytic conduction in wet weather or all together in a manner difficult to recognize. Old cement is a decidedly porous body that must also tend to swell and produce large mechanical stresses when foreign crystals have been deposited in its pores. It is thus seen that porous porcelain must eventually fail as an insulator. Likewise the porosity of the cement used in attaching the caps and pins must, for much the same reason, be a cause that aids in bringing about the failure of an insulator with time. It is said that the high grade electrical porcelain is fired to cone twelve temperature, 1355 deg. cent.[4] The maker claims that an underfired body will be tough and mechanically reliable and an overfired body will be brittle and mechanically unreliable. It is a well established fact that high-grade porcelain underfired is decidedly porous and unfit,[1] that from an electrical viewpoint only, fully fired porcelain has its pore systems amply closed (rendered vesicular) and overfired porcelain bodies are apt to have a "bleb" structure due to the concentration of gases sealed up in the pore system or to the evolution of gases in reactions that may occur.[1]

In view of these things it should not be permitted to meet mechanical loading requirements by the expedient of underfiring which is bound to reduce service durability. The assumption that the cracking of insulator porcelain bodies may be avoided by annealing[7] and by form design must in time be a disappointment if porosity of porcelain and of cement is permitted.[8]

The foregoing considerations indicate that acceptance tests must include a practical porosity elimination test as soon as it can be devised. Professor Creighton has indicated[9] and the work reported in the present papers shows that slightly porous porcelain does not by all ordinary means admit moisture quickly to any considerable portion of the body. It is true that ceramists take the amount of water absorbed by a porcelain as a measure of its porosity. However, unless the test specimen is thin it is broken into small fragments before being immersed in water. Even so it is quite likely that the best porosity measuring technique of the ceramist will have to be improved upon in order to measure with fair exactness the low values of porosity that occur in high-voltage porcelains offered for acceptance. The above remark, that it is ordinarily difficult to cause water to penetrate slightly porous unglazed porcelain, applies only to porcelain in bulk of insulator size.

The hunt is being continued for methods by which slightly porous porcelain can be made to take up water quickly to a considerable depth thereby correspondingly decreasing the insulation resistance and thus to determine electrically the existence of the porosity without injuring the insulator. The following tests were applied to unmounted insulators having caps unglazed inside and out and which were known to be porous because their resistance rose through oven treatment. The last method tried and here listed for detecting porosity did not involve water absorption:

1. Two insulators were immersed in live steam for four hours without result as to moisture absorption.

2. They were immersed in live steam for four hours during which cold tap water was circulated through the interior of the caps without moisture absorption result.

3. Using tap water electrodes, 25,000 continuous volts were steadily applied through the cap of one of these units for a period of two hours during which the current flowing was observed in the high-duty megger outfit. No change in the resistance of the insulator occurred, showing that moisture could not have been driven to considerable depths by the electrical and capillary forces during the time of the test.

4. A trial suggested by Mr. J. P. Jollyman: Dried porcelain known to be porous and non-porous insulators were megged, using 10,000 continuous volts applied through the outer layer of the cap and megged again after soaking in tap water over night. The overnight soaking caused the resistance of the porous insulators, only, to be lowered decidedly.

5. The caps of dry unmounted porous and non-porous insulators were subjected to ten kilovolts, sustained uniformly at 325,000 cycles per second for five minutes. Temperatures of the outer crowns of the caps were taken immediately before and after the test. After immersion over night in tap water the tests were again repeated. The heating of the dry porous insulators

was slightly more than of the dry non-porous while for those soaked in water over night the heating was decidedly greater for the porous than for the non-porous insulators.

6. Trial by gaseous conduction in lieu of electrolytic conduction: Dry porous and non-porous insulators were megged again with all conditions the same except that the electrode facing the outer surface of the caps was constituted of ionized gas liberated from an adjacent needle point connected to the galvanometer and properly guarded. The results showed that slight porosity can not be located by this method.

A look into the Transactions of the American Ceramic Society reveals the fact that ceramists have, in recent years, conducted several investigations of electrical porcelains that are of interest to transmission engineers. As the contents of these transactions do not appear to be generally known the author ventures to present certain diagrams and abstracts taken from these papers.

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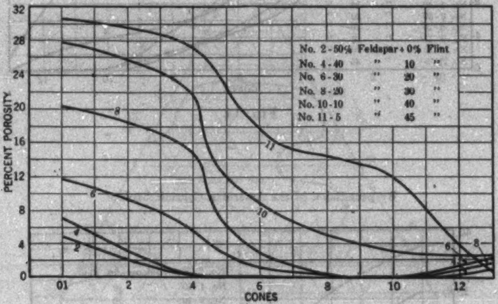

FIG. 13

In a study of explorations to find porcelains that should be suitable for high-voltage insulators at the University of Illinois, Bleininger and Stull[2] made up about 450 separate and distinct specimens of clays, spars and flints varying in kind and proportions. By permission of the American Ceramic Society Figs. 13, 14, 15, 29, 30 and 31 of the original paper are reproduced herewith. The first three are *porosity-temperature-composition* diagrams and the last *three* are corresponding triaxial diagrams in

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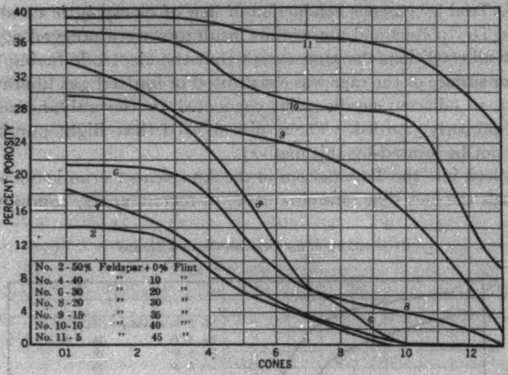

FIG. 14

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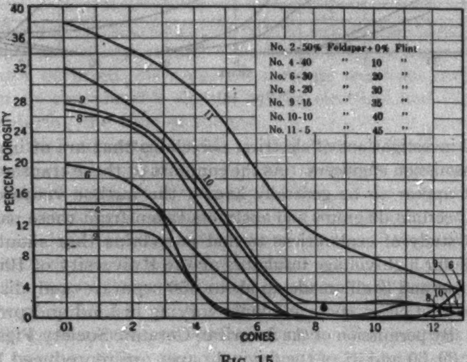

FIG. 15

which the *dielectric strength* (by slowly applied voltage required to puncture under oil) and *composition* are coordinated topographically. These diagrams are self-explanatory though a few corresponding quotations from the paper are helpful.

"All porcelain bodies absorbing not more than 0.1 per cent of water, by weight, upon boiling in vacuo are considered vitrified."

"*Tennessee Ball Clay.*" "The less refractory character of this clay is indicated by the large range covered by the temperature area below cone 10, (1305 deg. cent.)". Figs. 13 and 29.

"*The North Carolina Kaolin* offers quite a contrast to the last material, in as much as its vitrification area is quite small at temperatures up to cone 10. The range is decidedly increased at the higher temperatures." Figs. 14 and 30.

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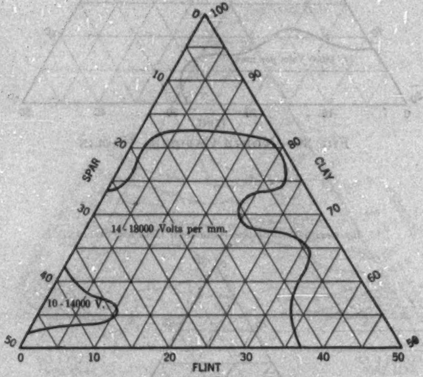

FIG. 29—TENNESSEE BALL CLAY

"*The English China Clay* differs from preceding clays in that its vitrification boundaries slope far more gradually in spite of the fact that its alkali content is not greater than that of the North Carolina kaolin." . . . "It is evident that this material differs considerably from similar American clays in this respect due to its structure or fineness of grain. Its vitrification area is quite large." Figs. 15 and 31.

"*Dielectric Behavior.*" The voltages have been arranged in *three* groups which are: less than 10,000 volts per mm., from 10,000 to 14,000 volts per mm., and from 14,000 to 18,000 volts per mm."

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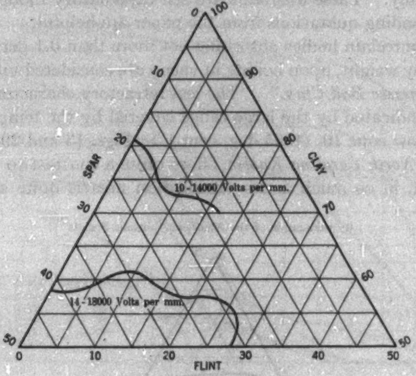

FIG. 30—NORTH CAROLINA KAOLIN

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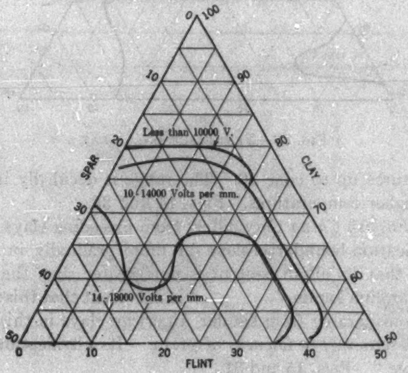

FIG. 31—ENGLISH CHINA CLAY

. . . . 'The electrical resistance (strength against puncture under oil) seems to depend more upon sound vitrification and good mechanical strength than chemical composition, excepting, of course, in so far as the latter governs the vitrifying behavior." Figs. 29, 30 and 31.

Later these studies were continued at the University of Illinois by B. S. Radcliffe under the supervision of Professor Stull.[11] A number of decidedly porous porcelains were found having (when dry) high dielectric strength. The results obtained are given in the triaxial diagram Fig. 5 of this paper, reproduced herein by permission of the American Ceramic Society. Used for high-voltage line insulators, however, these porcelains would in time become water-logged and salt laden and would eventually fail. Nevertheless the results are deemed of real importance to the transmission engineer for they corroborate the corresponding fact reported in the present set of papers and earlier by Bang,[12] viz. that dry porcelain when decidedly porous may possess a fairly high dielectric strength. Initial dielectric strength can, therefore, be no complete measure of the electrical service durability of a high-voltage line insulator.

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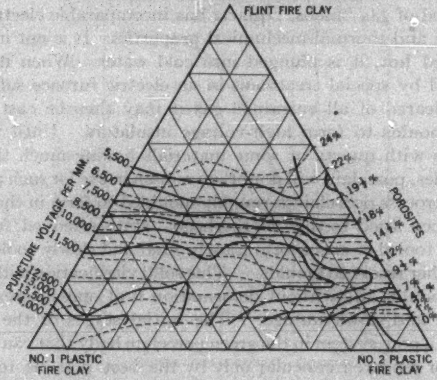

FIG. 5—RELATIVE POROSITIES AND DIELECTRIC STRENGTH OF FIRECLAY MIXTURES BURNED TO CONE 12½

In a critical study of the foregoing results in ceramics one is brought to the conclusion that the desirable qualities in electrical porcelain, refractoriness and, therefore, toughness and vitriousness or imperviousness, are to be gained only through a high content of flint fired at an amply high temperature.[15] Fused flint, quartz or silica as it is variously called is thus indicated as the limiting outcome of the use of more flint and less spar and clay. Quartz goes gradually into fluidity only at a higher temperature than platinum. In giving up its crystalline structure through heat it is subject to an extraordinary degree of cracking, whereby it captures large quantities of air or other gases in the furnace.[16] It is difficult to fluidify the quartz without evaporation sufficiently to liberate such entrained gases. These difficulties have been overcome in recent years sufficiently so that chemical ware of fused quartz can now be afforded to a limited extent. Once fused and freed of gas "blebs", quartz has incomparable electrical, refractory and thermal-mechanical properties. It is not injured if when red hot, it is plunged into cold water. When it can be fluidified by special treatment in an electric furnace sufficiently to be cleared of all entrained gas it may then be cast in cold metal moulds to form high-voltage insulators. Until this can be done with quartz or some materials having much the same properties, porcelain will doubtless remain in use for such purpose.

Wet process porcelain is roughly moulded to form in the plastic state, then dried to the "leatherhead" state, removed from the moulds, tooled to exact form, slowly fired and slowly cooled without further resort to moulds. This solid vitrification without the use of moulds and without deformation is at once its greatest advantage and disadvantage. The initial stages of the process develop a pore system in the green porcelain body that can be eliminated or rendered vesicular only by the best possible technique applied to each and every piece in all stages of the process. Since this is not practicable on a large scale it is inevitable that, in the factory production of high grade electrical porcelain some of the low grade must be produced along with it. The importance of all improvements and of tests for the elimination of structurally imperfect and appreciably porous porcelains and of the operating strategy of thoroughly shuffling the finished insulators so as to minimize the likelihood of more than one unrecognized defective insulator being mounted in the same string is made manifest by a study of these results obtained by the ceramists.

An investigation by Weimar and Dunn[13] undertaken in the department of ceramics of the University of Ohio yielded valuable knowledge as to the manner in which insulating qualities of porcelains vary with temperature. They give a table found in the Transactions of the Royal Society of London. It includes temperatures and corresponding specific resistances of a "porcelain" ranging from 1.63 deg. cent. to 81.93 deg. cent. Inspection of the contents of the paper reveals the fact that porcelain as here reported lost resistivity within the stated temperature range at the uniform logarithmic rate of 100 to 1 for the actual values in a rise of temperature of 51.2 deg. cent. The corresponding average value obtained from the results of Professor Clark as reported in his present paper is 46 deg. cent. rise in temperature. Considering the circumstances these resistivity-temperature relations are in fair agreement.

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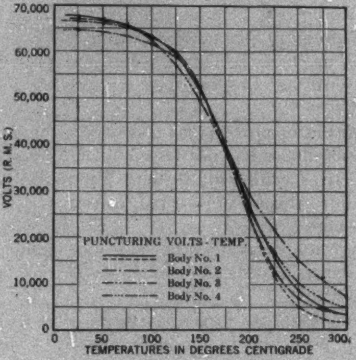

FIG. 6

Weimar and Dunn state that their work "covered that region known as the 'critical temperature' or that temperature at which porcelain ceases to be an insulator and becomes a conductor and to a small extent the effect of composition upon the same." The results obtained are charted in Fig. 6 reproduced from the paper by permission of the American Ceramic Society. The test specimens were cup-shaped 0.15 in. (3.8 mm.) thick heated in an open "electric furnace" and punctured with 60-cycle voltage steadily increased to the rupturing value.

Having in mind the heat resisting duty that porcelain in high-voltage insulators is expected to render when some forms of line "trouble" occur, it is a shock to one when he comes across these results for the first time. Above 300 deg. cent. it was found that the porcelains retained virtually no dielectric strength and that all applied voltage was consumed in setting up current through the test specimen functioning as an electrolytic conductor.

ACKNOWLEDGMENT

The author's study of the service durability of high-voltage suspension insulators would not have been feasible without the advice, helpful discussion and hearty cooperation of the following engineers, Messrs. J. E. Woodbridge, J. P. Jollyman, H. A. Barre and J. A. Koontz.

CONCLUSIONS

1. Appreciably porous porcelain should not be employed for suspension insulators. Under the action of the elements their failure must occur in due course of time.

2. Cement used for setting up cap and pin-type suspension insulators should be non-porous or rendered non-porous for reasons set forth.

3. Recognition of porosity as a contributing cause of suspension insulator failures has not lessened the importance of design features that reduce cracking through differential thermal expansions and failure through electrical overstresses and the heat of heavy flash-overs.

4. Defective materials in otherwise well designed and manufactured insulators have been responsible for most of their service-durability failures.

5. Clear fused quartz appears, technically, to be a desirable substitute for porcelain in the construction of suspension insulators.

REFERENCES AND NOTES

1. A. V. Bleininger. The Temperature-Porosity Relations of Clay Prepared in the Plastic and in the Moist Condition. Trans. Am. Ceramic Society, Vol. XV, p. 570, 1913.

2. A. V. Bleininger and R. T. Stull. A Study of the Vitrification Range and Di-Electric Behavior of Some Porcelains. Trans. Am. Ceramic Society, Vol. XII, p. 628, 1910.

3. Entectics formed by Minerals. See p. 79, Vol. XIII, Trans. Am. Ceramic Society, 1911.

4. B. S. Radcliffe. Investigations on Dielectric Strength of Some Porcelains. Trans. Am. Ceramic Society, Vol. XIV, p. 575, 1912.

5. Ross C. Purdy, Fluxes and Fusion. (President's Address). Trans. Am. Ceramic Society, Vol. XIII, p. 75, 1911.

6. C. E. Henderson and G. O. Weimer. Effect of Temperature on the Dielectric Strength of Porcelain Insulators. Trans. Am. Ceramic Society, Vol. XIII, p. 469, 1911.

7. Trans. Am. Ceramic Society, Vol. XIII, p. 404, 1911. Discussion: "Slow cooling has the same effect in vitrified china as annealing does in glass. If cooled slowly, we obtain a tough body; and if cooled too rapidly a brittle body. While the composition is important, slow cooling is equally as important a factor."

8. An examination of the engineers' records for more than 1000 of each of two lots of well known makes of insulators was made with respect to service durability. One lot had been made and put into service on a 100-kilovolt line, about *eight* years ago. The other lot was ordered, manufactured and delivered and stored in the open *four* years ago. They did not differ, essentially, so far as the author can see, in mechanical-thermal design features. The porcelain in the older lot was of a decidedly finer grain and less absorbent under the ink test than the newer lot. In the first *six* and *one-half* years of service, *one* and *one-half* per cent of the older lot failed. During four years in storage, *twenty* per cent of the newer lot had failed by megger test, or did fail on the application of sixty-cycle spark-over test.

Laboratory experience demonstrates that porcelain insulator bodies are subject to cracking when heated and cooled for the removal of absorbed moisture without hardware attached. For example: Three decidedly porous and water-logged insulators, *B M*4, *B M*30 and *U B*18, were heated slowly in a drying oven to 150 deg. cent. and held there for five hours. The source of heat was then cut off and the oven door opened to allow the insulators to cool. The oven being small, *U B*18, unmounted, had to be taken out when the door was opened. Its rate of cooling was naturally somewhat more than for the others. After being in the open air of the room for a few minutes, it cracked from the edge of the dish to the base of the cap. On close examination, several checks or small cracks in the inner wall of the cap were found, that evidently had occurred earlier. Before drying out, all of these insulators were so water-logged by immersion that they megged so low (a few megohms) that it was known in advance they would not sustain flash-over voltage. After drying out in two stages of about five hours each, the above was the second stage, *B M*4 and *B M*30, mounted insulators, megged with 20,000 volts, continuous, 580 megohms at 11.4 deg. cent., and 3.3 megamegohms at 11.7 deg. cent. respectively. The *B M*30 insulator was then subjected to 60-cycle *spark-over* voltage and endured 20 heavy spark-overs. The *B M*4 insulator has the characteristic of holding on to absorbed moisture tenaciously and must, therefore, be given further oven treatment before the spark-over test should, be applied. (Later, *B M*4 was given another 5 hour treatment in the oven. When cool it megged 1.6 megamegohms, 13.1 deg. cent. It withstood without apparent injury 12 heavy spark-overs at 83 kilovolts, 60 cycles.)

9. E. E. F. Creighton. *Experiences in Testing Porcelain Insulators.* TRANS. A. I. E. E., p. 739, this volume.

10. J. Minneman. Note on the Vitrification Range and Dielectric Behavior of Some Porcelains. Trans. Am. Ceramic Society., Vol. XIII, p. 704, 1911.

11. B. S. Radcliffe. Investigation of Dielectric Strength of Some Porcelains. Trans. Am. Ceramic Society, Vol. XIV, p. 575, 1912.

12. A. Bang. *Four Years' Operating Experience on a High-Tension Transmission Line.* TRANS. A. I. E. E., Vol. XXXIV, Part I, 1243, 1915.

13. George Weimer and C. T. Dunn. The Effect of Temperature on the Dielectric Strength of Some Porcelains. Trans. Am. Ceramic Society, Vol. XIV p. 280, 1912.

14. The Genesis of Asbestos and Asbestiform Minerals. Stephen Taper, Ph. D. Paper to be presented Feb. 1917 meeting, American Institute of Mining Engineers.

15. "That the toughness of a porcelain is dependent more upon the amount of flint present than upon either of the other two ingredients and that within the limits of this research the percentage of flint to be used for a strong porcelain should be very close to 35. With 35 per cent there seems to be a wide range in variation of clay and feldspar which produces tough bodies." Trans. Am. Ceramic Society, Vol. XIII, p. 395.

16. Vitrified Quartz. Lecture Royal Institution of London. W. A Shenstone, F. R. S., Nature, May 16, 1901.

17. The Effect of Varying the Sizes and Percentages of Quartz Grains upon the Porosities and Shrinkages of Kaolin. S. L. Gaplin. Trans. Am. Ceramic Society, Vol. XII, p. 54.

18. Note on Relation of Porosity and Crushing Strength of Clay Products. A. V. Bleininger. Trans. Am. Ceramic Society, Vol. XII, p. 564.

19. Origin of White Residual Kaolins. (President's Address.) Heinrich Rus. Trans. Am. Ceramic Society, Vol. XIII, p. 51.

20. Methods Employed in Connection with the Reduction, Milling and shipment of Quartz, Flint Rock or Silica Sand. Harry F. Speir. Trans. Am. Ceramic Society, Vol. XIII, p. 326.

21. Effect of Composition on the Strength of Porcelains. Lester Ogden. Trans. Am. Ceramic Society, Vol. XIII, p. 395.

22. Melting Point and Deformation of Entectics. Homer F. Stanley. Trans. Am. Ceramic Society, Vol. XIII, p. 668.

23. The Melting points of Pyrotechnic Cones Under Various Conditions. Sam'l. Geijsbeek. Trans. Am. Ceramic Society, Vol. XIV, p. 849.

24. The Relation of the Crushing Strength and Porosities of Clay Products. G. H. Brown. Trans. Am. Ceramic Society, Vol. XIV, p. 292.

25. The Effect of Overburning on the Structure of Clays. A. V. Bleininger and E. T. Montgomery. Trans. Am. Ceramic Society, Vol. XV, p. 71.

26. The Melting Points of Refractory Materials. C. W. Kanolt. Trans. Am. Ceramic Society, Vol. XV, p. 167.

27. The Function of Time in the Vitrification of Clays. G. H. Brown and G. A. Murray. Trans. Am Ceramic Society, Vol. XV, p. 193.

28. The Hydration of Portland Cement. A. A. Klein and A. J. Phillips. Trans. Am. Ceramic Society, Vol. XVI, p. 313.

29. The Legal definition of Vitrification. Edward Orton Jr. Sec'ty. Am. Ceramic Society, Trans. Am. Ceramic Society, Vol. XVI, p. 497.

30. Ceramics. The Constitution and Microstructure of Porcelain, by A. A. Klein, Bureau of Standards. (Summary communicated by the director of the Bureau of Standards, Dr. S. W. Stratton, details to appear as Bureau of Standards Technologic Paper No. 80) Journal of the Washington Academy of Science, Vol. VI, page 658, November 19, 1916.

Presented at a section meeting of the American Institute of Electrical Engineers, San Francisco, Cal., November 24, 1916.

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EXPERIMENTS ON PORCELAIN SUSPENSION INSULATOR UNITS

BY J. CAMERON CLARK

Abstract of Paper

The author gives a very complete description of the experiments on porcelain suspension insulator units carried on at Stanford University by him and his assistants under the direction of Prof. H. J. Ryan. He explains the preliminary organization necessary, the scope of the tests, and the unusual equipment required to measure the very high resistance of sound, dry insulators. Preliminary resistance measurements were made on all normal batches of porcelain units and the results tabulated, as also were results obtained when the units were subjected to mechanical stress, to voltages ranging from 1,000 to 30,000, to temperature variation. Another set of tests was made to determine the effect of moisture in insulators. Drying insulators for a few hours in an oven at 150 deg. cent. produced very conclusive results of the effect of moisture in lowering resistance. Attempts were made to water-log units by soaking, by soaking with a temperature cycle applied, by subjecting units under various conditions to a steam pressure of 60 lb., and by a vacuum treatment of insulators before soaking. A brief statement is given of the conclusions arrived at.

Introduction, Origin of, and Organization for the Work

The Work of Prof. Ryan. The work of Prof. Harris J. Ryan at Stanford University in the winter of 1915-16 demonstrated both the feasibility and the desirability of measuring the insulation resistance of suspension insulator units having resistances in the range between 5000 megohms and several millions of megohms. To illustrate: It was shown by Prof. Ryan that certain units having insulation resistances of, say, 15,000 megohms could be punctured in the air on 60-cycle voltage. The ordinary portable megger of 5000-megohms maximum scale reading will give a reading of infinity for such a unit, as it is unable to differentiate between units of 6000 and 1,000,000 megohms, whereas a dry, sound porcelain insulator will have a resistance of the order of 1,000,000 megohms or one "megamegohm". Prof. Ryan also disclosed the fact that some units become much lower in insulation resistance when subjected to prolonged soaking in water.

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*These values, as well as all other resistance values contained in this paper, are referred to a temperature of 20 deg. cent. unless otherwise mentioned.

Organization for tests. This work stimulated much thought among high-voltage engineers and, in particular, it aided in crystallizing a desire among them to develop a method by which it would be possible to detect faulty units with certainty, thus rendering it possible to avoid their installation. Accordingly, a committee of engineers was formed in May, 1916 to undertake experimental investigations of suspension insulator units, having as their broad purpose the production of test methods by which to detect with certainty and celerity all units which are electrically weak. Obviously, there is much difference of opinion on the classification of insulators as electrically "weak" and "strong". It is held by the committee, however, that any unit which is either weak at time of test or gives any indication whatever of the capability of developing weakness through lapse of time is to be condemned as weak.

The financial support of the work has consisted in contributions from a number of the California power companies. These companies, besides certain insulator manufacturers, have contributed liberally in test-specimens which will be found illustrated and briefly described in connection with "Preliminary Resistance Measurements".

The facilities of the electrical laboratories of Stanford University were placed at the disposal of the committee during the three summer vacation months of June, July, and August, 1916; and the writer and assistants were employed during this period to prosecute the testing work.

EXPERIMENTAL WORK

Scope of Tests. In addition to the measurement of the insulation resistance of every insulator unit in the condition in which it arrived at the laboratory, the summer's work consisted largely in attempting to determine the influence of certain important physical conditions of the insulator units upon their insulation resistance. The physical conditions which have been thus investigated are; mechanical stress, electrical stress (using continuous voltage), temperature, absorbed moisture.

The High-Voltage Megger. Since the resistance of a sound, dry porcelain insulator at ordinary air temperature is exceedingly large (of the order of 10^{12} ohms), it became necessary to provide rather unusual equipment with which to measure this quantity. Without entering into a discussion of the possible apparatus for this purpose, it may suffice to say here that it was decided to employ 25,000 volts continuous pressure current through the insulator, and to use as sensitive a D'Arsonval type galvanometer as could be had conveniently, to measure the current.

The pieces of apparatus which, taken collectively, may be called the high-voltage megger are shown diagrammatically in Fig. 1. T_1 is a 33-kv. transformer which supplies charge to the air condenser *C*, at high voltage through the kenotron *K*. T_2 is an insulating transformer through which the heating current is furnished to the cathode filament of the kenotron. The continuous high voltage is impressed upon the insulator at *S* through the resistance *R* which is provided as a protection to the kenotron against a possible short-circuit of the load at *S*. *R* is adjusted to allow only full-load current for the kenotron to flow on such a short-circuit, and with 25,000 volts on the circuit. The galvanometer *G* is connected in the test circuit next to ground. The connections from the low-voltage side of the insulator to the galvanometer are described in detail below.

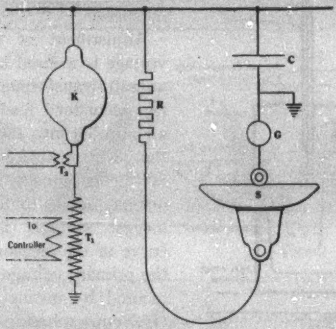

Fig. 1—High Voltage Megger—Connection Diagram

The use of 25,000 volts on the insulator results in an amount of surface leakage vastly in excess of that which occurs with the 600 to 1000 volts ordinarily used in megger tests. Most of this leakage is in the form of corona, and hence cannot be eliminated by any amount of careful cleaning of the surface of the insulator.

Vol. 35
1916

It is accordingly necessary to conduct all such strays directly off to ground by a path around the galvanometer. Fig. 2 shows the scheme used. Whenever possible, ordinary tap-water is used to make connection to uncemented porcelain blanks, and to make guard-rings, as it is very convenient in application. With units unprovided with petticoats, a felt ring saturated with water is laid on as a guard-ring, and the can guard is set directly on top of this felt ring. A grounded lead sheath protects the entire length of the wire running from insulator to galvanometer, while the instrument is remote enough from the high-voltage parts of the circuit to be immune from stray currents through the atmosphere.

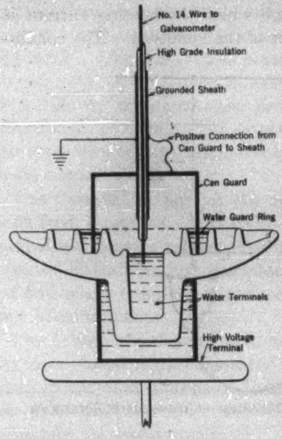

FIG 2—DETAILS OF GUARDING SCHEME

Adjustment of the megger voltage is secured by means of an auto-transformer with multi-tap secondary feeding through a controller into the primary of the 33-kv. transformer, while a voltmeter connected across this primary serves to determine the megger voltage, a calibration curve of the megger in terms of the primary voltage having been secured by means of a 7-inch (17.7-cm.) sphere gap.

Preliminary Resistance Measurements. Table I is a summary of the resistance measurements made on all of the normal batches of porcelain units immediately upon their arrival at the laboratory. The *UK* units are uncemented blanks of the same make and year as the assembled units of the *J* series. The *U H* units are blanks corresponding in every way to those used in the assembled *H* units. The photographic reproductions, Figs. 3 to 10 inclusive, illustrate all the types of units listed in the table. Table I also contains letters designating which insulator units are from a common maker. To illustrate: Units *G*, *H*, and *H M* were all made by the same manufacturer, *C*. It will thus be seen that the porcelain products of four different makers, *A*, *B*, *C*, and *D* are represented in the tests.

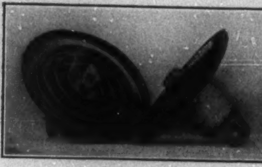

FIG. 3

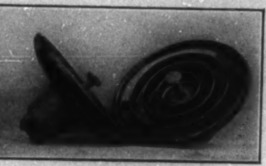

FIG. 4

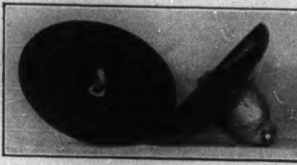

FIG. 6

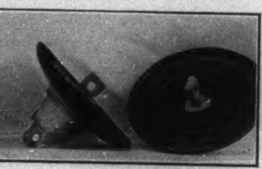

FIG. 5

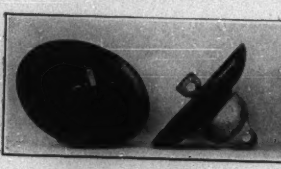

FIG. 7

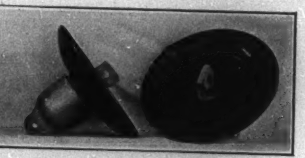

FIG. 8

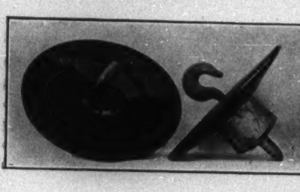

FIG. 9

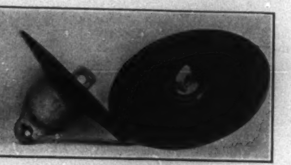

FIG. 10

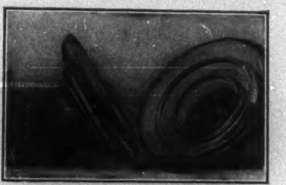

FIG. 13

CLARK]

TABLE I.

MEGAMEGOHM CLASSIFICATION OF PORCELAIN INSULATOR UNITS

(Compiled from insulator resistance measurements made on units as they were first received.)

Series	*A*	1 *A*-13 *A*	*C*	*J*	*U K*	*B*	*B L*	*G*	*H* and *UH*	*H M*	Q_1	Q_2
Figure	3	3	3	5	5	4	4	9	10	6	7	8
Maker	*A*	*A*	*A*	*A*	*A*	*B*	*B*	*C*	*C*	*C*	*D*	*D*
Date of manufacture	1912	1912	1913	1916	1916	1916	1913	1908	1916	1915	1916	1916
Megamegohm classes												
Below 0.010	..	1	..	..	..	..	3	..	..	..	..	..
0.010–0.099	..	3	..	1	..	..	..	..	..	..	..	..
0.10 –0.19	..	..	..	..	..	..	..	..	..	1	1	..
0.20 –0.39	1	1	5	2	..	..	1	..	54	9	..	..
0.40 –0.59	1	3	5	..	..	8	..	..	37	..	..	1
0.60 –0.79	2	32	17	1	4	90	..	..	3	1	1	40
0.80 –0.99	48	29	33	7	4	7	1	1	..	2	1	7
1.00 –1.19	40	20	12	51	4	..	8	5	3	8	28	..
1.20 –1.39	7	8	17	33	4	..	39	4	3	13	17	..
1.40 –1.59	3	2	..	22	..	..	31	4	..	2	1	..
1.60 –1.79	..	1	..	5	..	..	7	29	..	1	..	..
1.80 –1.99	..	..	..	1	..	..	11	33	..	1	..	..
2.00 –2.19	..	1	..	1	..	..	4	14	..	..	..	..
2.20 –2.39	..	..	..	..	..	..	1	7	..	..	..	..
2.40 –2.59	..	..	..	..	..	..	..	3	..	..	..	..
Total	102	101	89	124	16	105	106	100	100	38	49	48

In addition to the units of Table I, reference is made in this paper to various members of three additional small groups of units; namely, the *U B*, *B M*, and *F* groups. Of these the *U B* and *B M* units are specially selected soggy specimens of the same make and date as the *B L* series of Table I. The *F* units are of a new material, not porcelain. Fig. 11 shows the temperature-resistance characteristic of this material as exhibited by unit *F* 5. Fig. 13 is a photograph of an *F* unit.

Pull-Resistance Studies. A testing machine was used to subject the units to mechanical stress to determine whether this would affect their resistance. Pulls ranging from 0 to 5000 lbs. (22679. kg.) were applied to each kind of unit, but in no case was there any change in resistance from that obtaining for the unit in the mechanically unstressed condition.

Voltage-Resistance Studies. Some work was done using the high-voltage megger to ascertain whether the resistance of a unit is constant over the range 1000 to 30,000 volts. In any case where this source has been used, there has appeared to be practically no variation in insulation resistance over the range mentioned. However, some earlier work was done in the megging of very soggy units in which continuous voltages below 750 volts were used in order to hold the galvanometer current down to safe values. In every case where such a unit was later megged on 25,000 volts, the resistance thus determined is much lower than that obtained on the lower voltage. Table II shows results thus secured.

TABLE II

Unit No.	Test Voltage	Resistance, megohms
B L 19	110 25,000	13,000 820
5 *A* 6	415 25,000	21,000 6,900
B L 105	625 25,000	13,000 8,300
B L 68	635 25,000	8,300 2,200
8 *A* 4	730 25,000	60,000 20,000
8 *A* 2	740 25,000	73,000 42,000

It is not clear why there should be a difference between the resistance values obtained for these units at low voltage and at high voltage since quite a variety of low- and high-resistance units tested over a range of 1000 to 30,000 volts have shown no variation of resistance over that range.

Temperature-Resistance Studies. Early in the work it was brought forcibly to the attention of the test force that the temperature of an insulator is a factor of the greatest importance in its behavior under the megger test. To illustrate this point, Table III is presented.

TABLE III.

Unit No.	Resistance as first measured, megamegohms	Resistance as later measured, 20 deg. cent. megamegohms
1 *A*3	1.25	1.03
1 *A*4	1.04	0.99
1 *A* 5	1.09	1.12
1 *A* 6	0.93	1.09
1 *A* 7	0.60	0.74
1 *A* 8	2.08	1.01
2 *A* 1	0.83	1.11

The second column gives results which were obtained before the influence of temperature upon the resistance of an insulator was fully appreciated. The units had been lying in the hot sun for about an hour for the purpose of drying following a washing which had been given them. They had then been brought into the laboratory and laid on the floor for various lengths of time ranging from 15 to 45 minutes before being megged. It was then assumed that the room temperature (25 deg. cent.) could be taken as the temperature of the units without much error. The third column gives later results obtained after the units had reached a carefully determined steady temperature of 20 deg. cent. The lack of concord between the results in the second and third columns shows clearly the necessity for more careful work in this respect and, together with other similar observations, indicated the need of making a rather careful study of the resistance of porcelain as a function of temperature. An oven was therefore constructed which makes it possible to heat up eight units simultaneously and to megg them conveniently one after another on 25,000 volts continuous. All units rest on a common grate upon which is impressed the high voltage. Eight low-voltage connections pass out through the thick heat-insulated wall of the oven to a terminal board at which the galvanometer lead is connected to any unit desired. The temperature is determined by 10 carefully calibrated resistance coils wound of No. 34 copper wire having heavy leads brought out for convenient connection to a Wheatstone's bridge. The coils are placed at the height of the porcelain of the units and are otherwise at locations so chosen within the oven as to make it possible to judge of the resistance of a unit with a precision ranging from 0.2 deg. cent. at 25 deg. to 1 deg. at 65 deg.

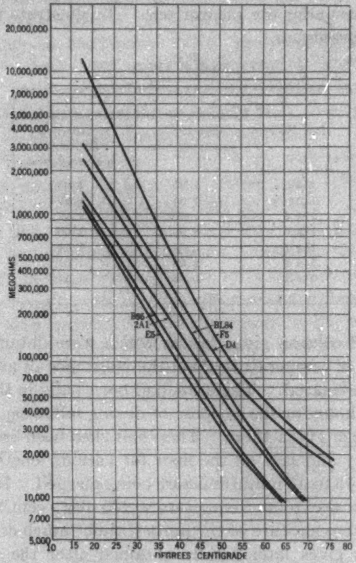

FIG. 11—VARIATION OF RESISTANCE WITH TEMPERATURE

The results of the study of six different insulator units are shown in the curves of Fig. 11. An exceedingly rapid rate of decrease of resistance with increasing temperature is shown by all the units, and this rate is substantially the same for all the different makes of porcelain insulators investigated. Fig. 12 is a curve derived from the temperature-resistance curves of porcelain units which has been found very useful in reducing to a common temperature basis of 20 deg. cent. resistance measurements made over a temperature range of 17 to 27 deg. cent.

Moisture in Insulators

Results of Drying Out Insulators. That some high-voltage porcelain absorbs enough moisture to lower its resistance is shown conclusively by the results of drying numerous insulator units for a few hours in an oven at 150 deg. cent. All the insulators investigated in this way fall naturally into three classes (see Table IV) as determined by the effect of the drying upon their resistance; viz., (a) those practically unaffected by any amount of drying, (b) those raised in resistance by 20 to 400 per cent, (c) those enormously raised in resistance, *i.e.*, hundreds or thousands of times. A result of this natural division of the units has been for the test force to call classes (a), (b), and (c) respectively "non-porous", " slightly porous", and "very porous".

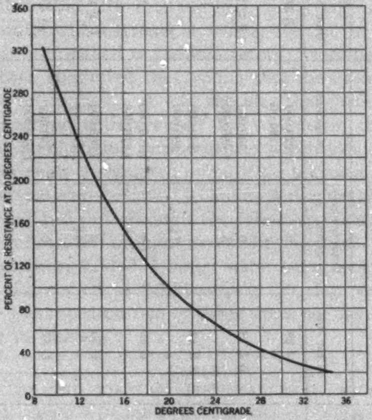

Fig. 12—Porcelain Insulator Temperature Reduction Curve

Attempts to Water-log Units. It is obvious that a very easy laboratory test for the detection of porosity in an insulator is the high-voltage megger test, *provided the insulator is already water*

TABLE IV.
RESULTS OF DRYING INSULATORS AT 150 DEG. CENT.

Class (a)			Class (b)			Class (c)		
Unit No.	Total hours drying	Megohms	Unit No.	Total hours drying	Megohms	Unit No.	Total hours drying	Megohms
B 56	0	700,000	*A* 29	0	220,000	*B M* 4	0	42
	6	750,000		5	1,180,00		7	1,470,000
B 69	0	690,000	*B L* 18	0	390,000	*B M* 30	0	2
	7	700,000		5	1,390,000		3	15,700
G 9	0	1,770,000	*U K* 12	0	730,000		5½	130,000
	8	1,790,000		7½	990,000		15	720,000
H 4	0	300,000	*G* 50	0	1,160,000		33	1,550,000
	6½	320,000		6½	1,610,000		43	1,670,000
U H 37	0	300,000	*G* 50	0	1,300,000	*U B* 14	0	2,080
	6	320,000		6½	1,720,000		4	770,000
U H 79	0	320,000	*G* 81	0	730,000	5 *A* 6	0	6,800
	7	320,000		6	1,610,000		7	1,130,000
U K 14	0	1,000,000	*G* 71	0	1,080,000			
	6½	950,000		6½	1,870,000			

logged. However, many, if not all, very soggy units (*i.e.*, units reading below infinity on the 5000-megohm megger) may be raised by a few hours drying to an apparently perfect condition in which they pass a 60-cycle dry spark-over test in air. It has accordingly been regarded as essential that a method be found by which porous units may be made to take up water quickly inasmuch as any test which consumes weeks or months of time in order to establish porosity cannot be considered to have practical or commercial value.

Early in the work, the soaking of porcelain units in water at ordinary atmospheric temperatures was undertaken, but it became evident that, by this method, water enters wet-process porcelain units with extreme slowness, even in the case of units which have been called in the laboratory, "very porous".

It was then suggested that, along with the soaking, a temperature cycle be applied. It was the idea that there might exist a sort of breathing action caused by volumetric changes of the material under changing temperatures which would draw water into the extremely attenuated pores of the porcelain. Accordingly, five units which were believed to have varying degrees of porosity were selected and put through the following cycle; Put into tub of water and water brought from 30 deg. cent. to boiling, 1 hour; water being boiled, $\frac{1}{2}$ hour; water being cooled to 30 deg. 1 hour, units cooled in "cold tank", (20 deg. cent.), $\frac{1}{2}$ hour. This cycle was repeated two or three times per day. The results are shown in Table V:

TABLE V.

"ACCELERATED SOAKING"—RESISTANCES IN MEGAMEGOHMS.

Total cycles	*U B* 3	*U B* 5	*U B* 13	*U B* 14	*U K* 13
0	0.75	0.73	0.0085	0.53	0.80
1	0.55	0.41	0.011	0.36	0.62
2	0.66	0.57	0.030	0.39	0.80
3	0.61	0.55	0.021	0.36	0.76
5	0.66	0.84	0.046	0.36	1.27

As shown by the table, the only positive effect of this process was to raise the resistance of some of the units treated. This is no doubt due to a rapid driving out of water from the porcelain during the boiling part of the cycle.

Another "accelerated soaking" test was next attempted in which the boiling part of the cycle was eliminated, the water being carried to a maximum temperature of 75 deg. cent. The same five units used in the previous test were subjected to this modified test. The results are shown in Table VI.

TABLE VI.

MODIFIED ACCELERATED SOAKING—RESISTANCES IN MEGAMEGOHMS.

Total cycles	*U B* 3	*U B* 5	*U B* 13	*U B* 14	*U K* 13
0	0.82	0.72	0.032	0.34	0.99
5	0.76	0.65	0.0039	0.18	1.01
8	0.71	0.63	0.0021	0.115	0.98
16	0.72	0.65	0.0011	0.072	0.94
24	0.82	0.66	0.00074	0.025	0.99

It is seen from Table VI that the rather porous units *U B* 13 and *U B* 14 are rapidly brought down in resistance by the 24 cycles of treatment, but that the slightly porous unit *U K* 13 has not been affected at all.

It was suggested that the entry of water into the pores of porcelain might be expedited by keeping one side of the porcelain exposed to the atmosphere while water is applied to the other, it being the theory that the application of water to both sides of the unit traps a certain amount of air within the pores effectually preventing the entire filling of the pores with water. To test this theory, two very porous units were selected and water was applied to one side of each. With a cemented unit, *B M* 30, the insulator was inverted and water was simply poured around the pin within the inner skirt of the unit and allowed to remain there for about two weeks. In the case of the other unit, *U B* 18, which is an uncemented porcelain blank, a rig was devised by which the pin cavity was filled with water and kept under 60 lb. per sq. inch (4.2 kg. per sq. cm.) pressure for about 30 hours. In neither case was there any material acceleration of the water absorption beyond that which would occur with ordinary soaking of the entire unit in water.

Since the negative results obtained in the application of water to one side of porcelain units may imply that the pores of the material are of such minute section that water enters them rapidly when in gaseous form, it was concluded to try the application of steam to one side of a porous unit. The test rig mentioned in the previous paragraph was therefore modified to permit the unit to be heated from the outside hot enough to generate steam within the pin cavity while the latter is kept filled with water at 60 lb. per square inch pressure. Thus steam at 60 lb. (27.2 kg.) pressure is applied to the inner surface of the pin cavity. Unit *U B* 18 was given two hours of this steam treatment. Megohm readings taken just before the test, and again as soon afterward as the unit had become cold are respectively 310,000 and 1050. This shows a remarkably rapid lowering of the resistance. This test was also applied to unit *U K* 13 which had been considered to be a slightly porous unit from the results of the first "accelerated soaking" test, see Table V. However, megger readings taken just before three hours treatment of the unit and afterward as soon as the unit had become cold show in each case a resistance of 0.85 megamegohms.

Vacuum treatment just before soaking has been tried with a number of units believed to be of varying degrees of porosity. The results of one such test are shown in Table VII.

TABLE VII.

VACUUM AND PRESSURE TREATMENT—RESISTANCES IN MEGAMEGOHMS.

Unit No.	Resistance in megamegohms			Remarks on previous status of unit.
	Aug. 16	Aug. 17	Aug. 18	
U B 2	0.00052	0.00028	0.00019	Considered "very porous" because of rapid lowering of its resistance in cold water soaking.
C 76	0.123	0.0101	0.0029	Considered "very porous" because its resistance lowered rapidly when stored on concrete floor in a cool place.
C 1	0.79	0.94	1.00	Considered "slightly porous" as its resistance rose decidedly when stored in a warm, dry place.
G 50	1.69	1.61	1.74	Considered "slightly porous" because its resistance rose somewhat due to drying in oven.
G 60	1.69	1.79	1.63	Same as *G* 50
G 71	1.69	1.50	1.61	Same as *G* 50
G 81	1.51	1.45	1.42	Same as *G* 50.

The values of resistance for Aug. 16 were obtained just prior to placing the units in the vacuum tank. On Aug 16, the units were put under a 25-inch (63.5 mm.) vacuum for 1½ hours, and while the vacuum was maintained, water was run into the tank until the units were covered. The water was allowed to remain over the units at atmospheric pressure over night (15 hours), and the results for Aug. 17 were then obtained. A 25-inch vacuum was again applied to all the units for five hours which was followed up immediately by water, the vacuum being maintained until the tank was filled with water. The water was kept under the supply pressure of 60 lb. per sq. inch above atmosphere over night (14½ hours), and the values of Aug. 18 were then obtained. As shown by the table, decided lowering of resistance occurred only in the cases of the "very porous" units.

With but two exceptions, the methods which have been tried in attempting to water-log units rapidly have been fairly successful in the cases of units known to be very porous. These two exceptions are the ordinary soaking in cold water and the attempt to accelerate water-logging by heating and cooling wherein boiling occurred during the cycle. However, no method has yet been found by which the slightly porous units can be made to take water rapidly. That efforts to this end have failed is remarkable in view of the fact that the water may be driven out of such units in a very few hours by heating them at 150 deg. cent. Whether these insulators would deteriorate in actual line service is a debatable question, the discussion of which lies outside the scope of this paper.

Conclusion

Much of the work of the summer has been concerned with the study of moisture absorption in porcelain insulators as indicated by their insulation resistance. This is largely due to the fact that few other characteristics of the specimens submitted have seemed so much worth while investigating as their porosity. In this connection, it is important to note that very little trouble with cracking due to expansion of metal parts is in evidence among the specimens, even among the older batches of units wherein little attention was evidently given to this subject. Some 60 assembled units of various makes have been subjected to temperatures ranging from 110 deg. to 150 deg. cent.—much higher temperatures than are ever encountered in service. Among these units were 30 selected as being most likely to crack owing to bad design wherein no provision was made at the base of the cap next to the disk for expansion of the cap. Out of the 60, only 3 units have failed by cracking; namely, Nos. *B L* 94, *C* 9, and *C* 76,— all of old design.

Inasmuch as the real factors which contribute to the weakness of many porcelain insulators are now much better appreciated, it is felt that some progress has been made toward achieving the broad purpose of the investigation; namely, to develop ready, sure and simple methods by which to detect the weak insulator. It is at the same time realized that a great amount of work remains to be done, and it is hoped that many others will devote themselves to this problem which it seems so necessary to solve if confidence is to attend the continued use of the porcelain high-voltage insulator.

Presented at a section meeting of the American Institute of Electrical Engineers, San Francisco, Cal., November 24, 1916.

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INVESTIGATION OF SUSPENSION INSULATOR DETERIORATION

BY J. E. WOODBRIDGE

ABSTRACT OF PAPER

This paper gives an outline of the investigation of suspension insulator deterioration undertaken by Professor H. J. Ryan and Assistant Professor J. C. Clark, and explained farther in their papers. It cites the origin of the investigation, the limiting factors encountered and methods employed to overcome such handicaps.

The results of this investigation are admitted as disappointing and inconclusive on the causes of deterioration, although several causes previously considered probable have been eliminated.

THE TROUBLES experienced by operators of high-voltage transmission lines, due to deterioration with age of the dielectric strength of cemented porcelain suspension insulators, combined with the inability of ceramists and engineers to agree upon a satisfactory explanation of such deterioration, have induced the power companies of California to join forces in a scientific investigation of this deterioration. The results of this study, in so far as results have been obtained to date, are presented in full in the accompanying papers by Professor Harris J. Ryan and Assistant Professor J. C. Clark. The companies interested in this investigation to the extent of contributing to the expense of same are; the Pacific Gas and Electric Company, Pacific Light and Power Corporation, Sierra and San Francisco Power Company, San Joaquin Light and Power Corporation, and the Southern California Edison Company.

The investigation began as the outcome of discussions on the subject between Mr. J. P. Jollyman, of the Pacific Gas and Electric Company, Mr. H. A. Barre, of the Pacific Light and Power Corporation, and the writer, representing the Sierra & San Francisco Power Company. These discussions resulted in a conviction that megohm values of infinity determined by the commercial megger, that is, anything above 2000 or 5000 megohms, covered a wide range of porcelain values, an investigation of which might develop insulation resistances characteristic of durable versus non-durable porcelain. It was even thought that if deterioration is due to porosity, and if suitable apparatus could be developed for measuring much higher insulation resistances, a characteristic resistance might be found for porous porcelain, even when dry. It is obvious that if these hypotheses had proved correct, it would be possible for insulator makers to measure such porosity by electrical means in new porcelain, and determine in advance what insulators would deteriorate, which would in turn allow them to determine what method of manufacture would produce the most durable product in this respect.

It was also the idea of these engineers that insulation resistance measurements made under dielectric stresses more nearly approximating those of commercial service than the 1000 volts of the commercial megger might be of correspondingly greater value. The inherent difficulties of such measurements with alternating voltages, due to the extremely low power factor of insulator leakage, at once suggested the use of the kenotron for the supply of continuous current at the voltages desired.

A paper presented by Professor Ryan before the San Francisco Section of the Institute on March 31, 1916, described such measurements made at Stanford University under a pressure of 4000 volts d-c. derived from a kenotron with a sensitive galvanometer, the combination giving a range up to 800,000 megohms distinguishable from infinity. This equipment as then developed by Professor Ryan obviously extended the range of meggering to values 160 times greater than those of the commercial megger. A further extension of this line of investigation was then proposed to Professor Ryan with the request that he obtain the consent of the University authorities for the use of the high-tension laboratory and its equipment for this study during the 1916 summer vacation. Professor Ryan obtained this privilege and agreed to serve as a member of the committee having charge of the work, to which service he devoted the greater portion of his time during the vacation period. The necessary funds were contributed by the above mentioned companies and the work was started under the direction of Professor Ryan, the above mentioned engineers, and Assistant Professor J. C. Clark, who was employed actively on the work with assistants throughout the summer. Insulators were contributed by the various power companies above mentioned and by the Great Western Power Company, also by several manufacturers, usually in lots of 100, these insulators being of all the well known makes, and, in so far as possible, of various ages, colors and previous conditions of servitude.

The results of this investigation to date may at the outset be admitted to be disappointing, as the ambitions of the promoting engineers have not been realized. Water logged elements have been dried out and restored to insulation resistances equal to those of the least porous. By the use of continuous current at 25,000 volts and of galvanometers of great sensitiveness, infinity has been thrown above the resistance of any single piece of porcelain procurable, measurements being possible up to ten million megohms. As might be expected, this has been accomplished only by the exercise of great care and ingenuity in the matter of guarding against leakage. The characteristic resistance of porcelain suspension insulators of common shapes and sizes has been found to run between one-quarter and one and three-quarters million megohms.

Conclusive positive information on the causes of deterioration has not been obtained, but considerable negative information has practically eliminated several causes previously considered probable. Mechanical loads have been proved to have little or nothing to do with the case. Stresses set up by expansion and contraction with temperature changes appear to have little or nothing to do with deterioration in properly designed and annealed elements. There are indications that these stresses are as great in insulators without attached hardware as in those complete with cemented metallic attachments; also, that such stresses are as great in porous insulators as in those more thoroughly vitrified.

A study of porosity has shown that much, if not all wet process electrical porcelain is slightly porous, some of this porcelain being more suitable for filtration use than for the exclusion of moisture. Aside from this exception, the term "slightly porous" here means porous to such an extent that moisture may in the course of years creep into minute crevices, forming conducting paths which eventually reduce the distance between terminals of the insulator, (Considering such paths as conducting extensions of terminals into the mass of the porcelain) until the dielectric stresses between terminals will rupture the intervening material. Local heating in the non-porous barriers separating such conducting paths probably assists the final failure of the remaining dielectric strength. This investigation has shown that porcelain has an extremely high negative rate of change of resistance with temperature. Of the specimens tested, the rate of change may be stated as a loss of 99 per cent of the resistance with a rise of 45 deg. cent. from ordinary temperatures.

This partial porosity has so far been found extremely difficult of detection. We have found it impossible to devise any means of materially hastening the absorption of moisture above the rate inherent in ordinary line use, which often requires several years before the deterioration is apparent.

The difficulty in making porcelain bodies absolutely impervious to moisture is obviously due to the fact that porcelain by the very nature of its formation cannot be completely liquified in the process of vitrification as can other materials, such as glass. This leads to the consideration of materials having the desired mechanical and electrical qualities, which can be liquified and cast in a mold. Of these the most promising in both electrical and mechanical characteristics that has been brought to the attention of the committee is fused silica. This material has a high dielectric strength, and an extremely low coefficient of expansion with temperature. Its behavior when subjected to high dielectric stresses of sustained high frequency gives promise of very desirable characteristics in the qualities of dielectric strength, local heating under high potentials, and change of resistance with temperature.

It is the wish of the committee that others investigating this subject, or in a position to do so, may benefit by the ideas developed by this committee's work to date, and may carry on the work along the various lines indicated, which this committee has not been in a position to carry to completion.

Presented at the Chicago Section meeting of the American Institute of Electrical Engineers, November 27, 1916.

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TEMPERATURE DISTRIBUTIONS IN ELECTRICAL MACHINERY

BY B. G. LAMME

ABSTRACT OF PAPER

The paper deals with certain fundamental principles governing heat distribution and temperature in electrical apparatus. The general problems of heat generation, heat flow and heat dissipation, upon which the resultant temperatures depend, are discussed at some length. The various paths of heat flow and the effects of the heat resistance of such paths are discussed. The effects of rapid heat flow on the equalization of the temperatures, and on their measurement, are considered briefly. Some of the fallacies in temperature guarantees and in temperature indications are pointed out. Some of the more common errors in the methods of measurement are described. In conclusion it is stated that no hard and fast rules can be made to cover the facts, except in a very general way, and that commercial temperature measurements should be considered as approximate, this being permissible because there is no sharply defined line between good and bad.

THE LAWS governing heat flow and temperature distribution are so similar, in many respects, to those governing electric current flow and electric potentials, that it is rather surprising that the former have received so little attention in comparison with the latter. Some of the laws of heat flow are so well recognized that their application to the problem of temperature distribution in electric apparatus should have been a leading feature in the early developments in such apparatus; whereas, on the contrary, it is only recently that very careful study has been made of such application.

One object of this paper is to indicate, in a comparatively simple manner, some of the conditions which fix the temperatures in different parts of electric apparatus. Before going into the general problem, certain simple conditions may be stated, such as:

1. The heat flow between two points is proportional to their temperature difference and to the heat resistance of the path or paths between them. Note the resemblance to Ohm's law.

As a corollary to the above, it should be evident that between two points at the same temperature, there should be no flow of heat.

2. The total temperature drop between any two points or media of different temperatures will be the same through all paths of heat flow.

3. There are no true non-conductors of heat, and, conversely, no perfect conductors.

4. Heat conduction and electric conduction bear some quantitative relation to each other, in the broad sense that all electric insulators are relatively poor heat conductors, while good electric conductors are correspondingly good heat conductors. There is apparently no rigid relation between the heat resistance and electric resistance of the various materials used in electric machinery, but the general relation holds and there are apparently no radical exceptions.

5. The rise in temperature at any point, due to generation of heat, is dependent (a) upon the total heat generated, and (b) upon the amount of heat which can be carried away along all available paths per degree of temperature difference. The temperature will rise until the heat dissipation equals the heat generation.

6. There are two ways to lessen the heat flow along any path. (a) By interposing higher heat resisting materials. (b) By lessening the temperature difference, as by raising the temperature of the part through which the heat is to be conducted. Conversely, the heat flow can be increased along any path by the use of better heat conducting materials, or by paths of lower heat resistance, and by lessening the temperature of any part to which the heat is to flow.

What makes the problem unduly complicated, in electrical machinery, is the fact that there are several different sources of heat generation, which may be, and often are, all active at the same time. Moreover, the heat losses may be distributed through the various heat conducting paths in such a way as to render any calculation very difficult and more or less inexact, except in a general way. For example, there is heat generated by losses in the copper conductors, obeying one law; while there is heat generated in the iron parts under a quite different law; and there may be heat generated by windage and friction, according to a third law. As these different losses may act in different parts of the heat conducting circuit, it should be evident that the problem of determining the exact heat distributions, and the temperature, is a very complex one. Such a determination is in the province of the expert analytical designer of such apparatus, but certain general conditions are of interest to all users of electric apparatus.

Consider first the general conditions of heat dissipation from an armature coil. In Fig. 1 is represented an armature slot with the surrounding iron, and with two separate "coils" per slot, as is now the most common practise. Let it be assumed that the point *a* represents the "hot spot", or part at highest temperature in the apparatus. The heat from this part can flow along two general paths, namely, longitudinally through the copper conductor itself to the end windings, and thence to the air, and laterally through the insulation to the surrounding iron, or to the ventilating ducts. From the iron the heat flow is then through various paths to the external cooling air.

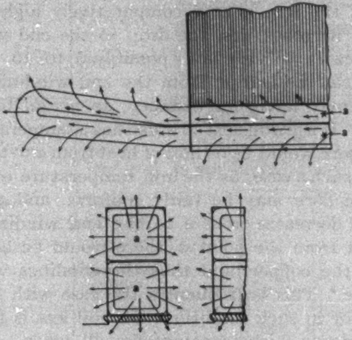

Fig. 1

Longitudinal Heat Flow

Considering first the longitudinal conduction of heat in the coil, then starting at the point *a*, the first unit of length conductor will have a certain loss. If the heat generated by this first unit loss were all that need be considered, then the drop in temperature, from the point *a* to the end windings, would be simply a function of the heat-conducting properties of the conductor itself. But the next unit length is also generating its own unit loss, so that the heat flow from the second to the third unit length is due to two units loss; in the same way, the flow to the fourth unit length will be due to three units loss, etc. Therefore, the temperature drop, or temperature difference per unit length of conductor, increases more rapidly as the point *a* is departed from, and if it is at a considerable distance from the end winding, and the losses per unit length are comparatively high, a very high temperature may be required at *a* to conduct all the heat longitudinally to the end windings. In very wide core machines the longitudinal drop may be so great that the temperature at *a* in practise will be so far above that of the surrounding iron, that a very large percentage of the actual heat is conducted laterally through the insulation to the iron, even if the iron is at a comparatively high temperature. However, in narrow cores, the drop to the end windings may be, in some cases, so very low, possibly 5 to 10 degrees, that with good heat dissipation from the end windings themselves, the point *a* may have, for instance, an actual temperature of 40 deg. cent. If the iron next to *a* also has a temperature of 40 deg. cent. then there would be no flow of heat from *a* to the iron. Furthermore, in such a case, as the iron temperature over the whole width of the core may be fairly uniform, and as the copper temperature decreases from *a* to the end windings, obviously as we depart from the point *a*, there would be heat flow from the iron to the copper, and thus the windings would tend to cool the core. This is frequently the case with light loads on a machine, for in such conditions the coil loss is low, while the iron loss remains fairly constant for all loads. In such case there may be heat flow from the iron to the copper along the whole length of the buried portion of the coil. At some higher load, the copper loss varying as the square of the load, the increased longitudinal drop will bring the copper temperature above that of the iron so that the heat flow is from copper to iron. This condition is illustrated by Fig. 2.

It must be recognized that the lateral flow of heat, from the coil to the iron, reduces the longitudinal drop, such reduction depending upon the relative percentages of heat flow along the two paths. It must also be borne in mind that in order to have such longitudinal heat flow, the end windings must be able to dissipate their own heat at lower temperature than would be attained at *a*, or in the core. If the end windings have little or no ventilation, or heat dissipating capacity, then their own generated heat may bring their temperatures higher than those of the armature iron so that the heat flow actually may be from the end windings toward *a*, and then laterally through the insulation to the core. In such case, the hottest spot will be in the end winding rather than in the buried part of the coil. Obviously when such condition occurs there is no possibility of either the end windings or the buried part of the coil being cooler than the iron, for the heat flow throughout is toward the iron.

Lateral Heat Flow

Considering next the lateral flow of heat through the insulation to the iron, the amount of heat conducted is a function of the temperature difference and the resistance of the conducting path. Or, in other words, if a given amount of heat is to be conducted through a path of given resistance, the temperature in the heat generating part will rise until the required heat is conducted away.

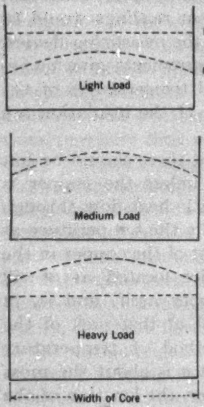
Iron Temp's.
Copper Temp's.
Light Load
Iron Temp's.
Copper Temp's.
Medium Load
Copper Temp's.
Iron Temp's.
Heavy Load
Width of Core

Fig. 2

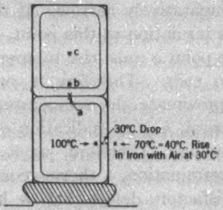
c
b
a
30°C. Drop
100°C.
70°C.-40°C. Rise
in Iron with Air at 30°C

Fig. 3

To illustrate this problem more concretely, let Fig. 3 represent the temperature conditions in a section of an armature. Assuming, for example, the temperature of the copper inside the coil insulation as 100 deg. cent., the iron temperature as 70 deg. cent., and the air temperature as 30 deg. cent., then the following conclusions may be drawn.

(a) From the outer coil (the one next to the air gap) through the wedge to the air gap, the temperature drop will be 100 — 30 = 70 deg. cent. Obviously, any temperature measurement made outside the wedge, next to the air, will approximate the temperature of the air and not of the copper. Any temperature measurement made beneath the supporting wedge will measure some intermediate temperature between the copper and the air. If the temperature drop through the wedge should be equal to that through the insulation, then a measurement underneath the wedge should show half the temperature drop through insulation and wedge, and obviously, the measured temperature would be far below that of the copper.

(b) If the temperature is measured at the outside of the coil, between the iron and the insulation, it would approximate the average of the temperatures of the iron and of the outside insulation, or practically the temperature of the iron. If the iron should be at different temperatures at the sides of the slot and at the bottom, then obviously different readings would be obtained, depending upon the location of the measuring device. It is evident that such temperature measurements give no indication whatever as to the true internal temperatures of the coil, for the heat flow and the resistance of the insulation are nowise involved in the measurement.

(c) At a point *a*, between the two coils, there should be but little heat flow through the insulation, unless the copper is comparatively narrow. If there is but little heat flow through the insulation at this point, then eventually the temperature at the point *a* must rise to approximately that of the copper in the two coils. Therefore, a measuring device located at *a* will approximate the temperature of the copper itself, and is, in general, a good indication of the hot spot at that part of the winding. Therefore, as a practical method of temperature determination, a thermo-couple located at *a* is about the most satisfactory device that we have. However, the location of the point *a* along the slot is also of importance on account of the longitudinal flow of heat in the conductor and the consequent temperature drop. In other words, the direction of heat flow in the coil itself, must be taken into account. Therefore, a thermo-couple located as above, is only satisfactory when the general location of the hot spot is known beforehand. This is usually determined, in a general way, for a given type or line of machines, by locating several thermo-couples along the slots.

With narrow slots and comparatively thin conductors, and especially with very heavy insulation, there is some flow of heat through the insulation which lies between the two coils, this heat passing out sidewise to the iron. In such case, the point *a* may be of somewhat lower temperature than the copper. It may happen also, in some cases, that, due to unequal losses and heating of the two coils in the same slot, one is at a higher temperature than the other. In such case, due to the heat flow between the coils, the temperature indication at *a* will not show better than an average of the two temperatures. Furthermore, if the temperature at *c*, in a coil subdivided into many insulated conductors, is materially higher than at *b*, then the temperature indication at *a* may not be a close approximation to the maximum temperature.

Flow Through Iron Parts

In the ordinary armature, after the heat passes from the copper to the iron, there is still quite a problem involved in the dissipation to the surrounding medium, which is usually the air. The direction of the heat flow to the iron will depend, to a considerable extent, upon the arrangement and location of the heat dissipating surfaces. There are two general paths of heat conduction in all armature cores; namely, a flow along the laminations to where their edges come in contact with the air or with other material, and a flow across the laminations toward heat dissipating surfaces. The flow along the laminations may be calculated with fair accuracy. Across them it is difficult to determine such flow, largely because the laminations are insulated from each other by materials which are poor conductors of heat. Also such flow is affected not only by the insulation between laminations, but by the perfection of contact. In other words, the heat flow may be affected by pressure. According to the various figures available, the heat flow per unit volume of material along the laminations is from ten to one hundred times as great, for a given temperature difference, as across them. Obviously, therefore, heat dissipation from the iron by flow across the laminations should be considered relatively inefficient, yet in the vast majority of rotating machines the heat dissipation is largely across the laminations. The reason for this is that by placing ventilating passages or ducts, parallel with the laminations, at frequent intervals in the core, the cross section of the heat path in the intervening iron sections, may be made very large compared with the heat to be dissipated, so that the density of flow is very low. By the same procedure the length of the heat path is made quite short. Thus in practise, the temperature drop through the laminations themselves may be made relatively small compared with other drops. However, not all the heat in the iron passes across the laminations to the ventilating ducts, for where the length of the path, along the laminations to any heat dissipating surface, is not large, a very considerable amount of the heat may be dissipated from the edges of the laminations themselves. In fact, in certain types of machines with very shallow iron cores, experience has shown that the ventilating ducts, parallel with the laminations, may be omitted, provided good ventilation is obtained over the edges of the laminations. It is evident, therefore, that the flow of heat and distribution of temperature are dependent upon the arrangement of the iron, dimensions and location of the ventilating surfaces etc.

HEAT FLOW TO THE AIR

After the heat has passed from the copper to the iron, the resultant of the copper and iron heats must be conducted to the cooling medium, which is usually the surrounding air. In the case of air, there is usually a considerable drop in temperature from the solid surface to the cooling air itself, the amount of such drop depending upon the ventilating conditions. In practise, there appears to be a film or layer of air which adheres very closely to the solid surfaces. This forms a sort of heat insulating film, retarding the flow of heat to the cooling air. In air ventilation, the effect of any considerable air movement over the surface appears to be that of scouring this hot film away from the surface and *replacing it with a film of cooler air*. Merely scouring or rubbing the hot film away from the surface is not particularly advantageous unless some means is furnished at the same time for supplying an ample quantity of cooler air to take the place of the removed hot film. Rapid air circulation, by means of a supply of air from the outside, appears to accomplish both results in one operation. Thus, one of the principal actions of air ventilation appears to be that of scouring away the hot contact film, while a second action is to carry the hot air away without mixing it with the incoming cooler air. Whatever portion of the dissipated heat is absorbed by the incoming cooling air adds that much to the temperature of the air itself and eventually to that of the apparatus to be cooled. Thus mixing the outgoing with the incoming air makes a sort of Siemens' regenerative furnace and the machine becomes cumulatively hotter and hotter until the dissipation through other paths becomes equal to the heat generated. In such cases the ventilation of the machine may only be useful in equalizing or redistributing the temperatures in the various parts.

From the preceding analysis, it would appear that the temperature at the hottest part of the coil is fixed principally by the heat flow through the copper, and its surrounding insulation, directly to the air, and by the flow from the copper to the iron, and from the iron to any exposed air surfaces, and then to the air. Along the first path, there are three principal temperature drops; namely, in the copper itself, then through the insulation, and then from the outside surface of the insulation to the air. Along the second path, there are also three temperature drops; namely, from the copper through the insulation to the iron, then from the iron to the exposed air surfaces, and then from the surfaces to the air. Along the first path each part of the copper path is generating its own heat, to be conducted away, in addition to that which is to be conducted from other parts of the path. In the second path, each part of the iron path may be generating its own heat, which adds to that coming from other parts. The relative amount of heat conducted along each path is dependent upon so many conditions, which vary with the load, that no one but an analytical designer backed by experience could even approximate the values by calculation. However, it should be obvious that any measuring device applied to the outside or cooling surface does not, and cannot, directly approximate the temperature of the hottest part, except in those rare cases where the hottest part is dissipating heat directly to the air. This is true only in very special cases such as series coils of bare strap, etc. In any coil or part of the apparatus which is heavily insulated, that is, which is covered by poor heat conducting materials, an external temperature measurement is an extremely poor indication of the true internal temperature, unless many other conditions are known which may give an indication of the internal temperature drops. In different types and constructions of rotating apparatus, hot spots may hold quite different relative positions with respect to the cores and windings, so that no reasonable rule can be made to cover all cases. Moreover, in some classes of apparatus, it is not practicable to make any temperature measurements until after the apparatus is shut down, and this introduces other very important errors which should be considered, such as cooling effects as a whole, during the period of shut-down, equalization of temperature due to internal conduction, etc.

EQUALIZATION OF TEMPERATURE, ETC.

When there are hot spots, or zones, or areas, of different temperatures, in an armature winding, for instance, such difference in temperature is maintained by the continual generation of heat in the various parts. But the moment that such generation of heat is stopped there is immediately a tendency for equalization of temperatures by flow of the stored heat from the hotter parts to the cooler. In good heat conducting materials, as copper, such equalization may be very rapid, so that a temperature indicating instrument of a sluggish type may not indicate anything like the true maximum temperature of the spot where it is placed, if applied after the load is removed, especially if the rate of heating of the thermometer bulb is much less than the rate of heat transfer from one part of the winding to another. If located on a hot spot, the reading may rise to some intermediate value and then drop off as the hot spot cools by heat conduction to other parts. If located upon a cool spot, it may rise slowly for a considerable period, due partly to sluggishness of the thermometer and partly to the cool spot rising in temperature by conduction of heat from some other part. The conditions are so varied that no reliable conclusions can be drawn, from the action of the thermometer alone, in regard to the coolest or hottest spot.

A second condition which tends to make such temperature measurements fallacious, lies in the cooling action in the interval between load removal and shut-down to take temperature measurements. In apparatus which depends upon a high degree of artificial cooling, such cooling effect may be very considerable. This is particularly true of high-speed machines which require considerable time to come to a standstill. It is, therefore, desirable in such machines to obtain all possible temperature readings at normal speed and with load. In rotating field machines, this is, to a certain extent, practicable, but in most rotating armature machines, the armature temperatures usually are not attainable until the machine is brought to a standstill, and even then some error may result from sluggishness or delay in taking the readings. One method which has been proposed at times, for lessening the sluggishness, is to heat the thermometers up to practically the normal operating temperature of the part to be measured, while the machine is still carrying load. At the moment of shut-down the heated thermometer is applied. This, to a certain extent, removes the factor of sluggishness in the thermometer itself, but is only a partial compensation. It must be considered that the outside of the insulation is at lower temperature than the inside, and that, therefore, the body of the insulation itself must have its temperature increased by flow of heat from other parts.

Fallacies in Temperature Guarantees and Measurements

In the older methods of determining temperatures, it was assumed that the thermometer readings, obtained on a winding, for instance, were a true indication of the temperature of the winding as a whole. The manufacturers of electrical apparatus long ago recognized the fallacy of this method, as they had found from bitter experience that there were liable to be hotter parts in the machine than any thermometer readings would indicate. They, therefore, designed machines with regard to the possible hot-spot temperatures as encountered in service, rather than any temperature which the exposed parts of the machine would show. Thus in designing a certain machine for safety at the hottest part, not infrequently the exposed parts of the winding would show, by thermometer, comparatively low temperatures, such as 25 deg. to 35 deg. cent. rise. Therefore, as the observable temperature readings came so low it became the fashion to call for 35 deg. cent. guarantees and, in many cases, the operating public lost sight of, or perhaps never knew, the real meaning of such low temperatures. Among the designers of electrical machinery, it was recognized that a temperature rise of 35 deg. cent. in itself was absurdly low, but that the object in operating at such low temperature on a part which could be measured was simply to protect the machine in some inaccessible hotter part, where the temperature could not be measured. From the present viewpoint, it is astonishing what reliance has been placed upon temperature readings in the past. For example, if a 40 deg. cent. machine showed 41.5 deg. cent. rise on test, it was unsafe, while if it showed 38.5 deg. cent. rise, it was good. We now recognize that neither of these temperatures have any controlling value, unless many other conditions are known. To the experienced man they simply mean that compared with the other machines of similar constructions and characteristics, which have proved satisfactory in service, they are reasonably safe. To the designer they mean that when proper corrections have been made for the various internal temperature drops, the highest temperature attained, at any point, will be within the limits of durability of the insulating material used. The whole problem is a good deal like that of a determination of the voltage generated in a given power-house, by measuring the voltage at the end of a transmission-line. If we know all the constants of the line, and know the current flowing, etc., we can figure back to the generated voltage. Otherwise the voltage at the end of the line means but little. However, we know that if the system is designed with reasonable regard to economy in general, there may be from ten to twenty per cent voltage drop from power-house to the end of the line. Therefore, by adding an approximate correcting factor to this voltage, we can make a reasonable estimate of the generated voltage. In the same way in electrical apparatus of certain types, a reasonable internal temperature drop may be approximated, which added to the observable temperature, gives a fair approximation to the hottest part, but *the result is an approximation and must be recognized as such*. Primarily, the manufacturer must make a safe machine for a specified service regardless of the temperature guarantees, and the temperature measurements made on most classes of apparatus should be considered simply as rough approximations to indicate that the manufacturer has made a reasonable attempt at a safe machine. This may seem a rather bald statement, but nevertheless it is a fair statement of the case.

ERRORS IN TEMPERATURE MEASUREMENT

It has been shown in the preceding that the usual observable temperatures are in most cases only crude approximations to the real temperature conditions. It may now be shown that even the observable temperatures, obtained by the usual means, are in themselves only crude approximations, in many cases. Take, for instance, the determination of temperature by increase in resistance; when the coil is heated its temperature may not be, and very frequently is not, uniform throughout the coil. As an extreme example, if one-fifth of the coil length has a temperature of 80 deg. cent., while four-fifths of it has a rise of 30 deg. cent. then the increase in resistance of the coil as a whole will correspond to a rise of 40 deg. cent. Thus, by increase of resistance, the temperature may be more than safe, while actually one-fifth of the coil is far above the safe temperature for ordinary fibrous insulations. In other words, the resistance method gives only average results and may be very misleading. However, in those cases where it is known, by past experience and otherwise, that there is very little liability of hot-spots, the resistance method of determining temperature is often quite satisfactory. However, the method is limited to comparatively few types of windings.

Considering next the thermometer method of measurement, the theory of this is quite simple, but apparently it has been very much misunderstood. In windings, except in rare cases, the thermometer is not applied directly to the heat generating material itself, but is applied outside of an insulating covering. Usually the temperature drop through this insulating covering does not receive any consideration, and yet everything depends upon this. Assume, for example, an insulated coil, thermometer and covering pad, as shown in Fig. 4. Assuming the copper inside the coil as being of uniform temperature, and the cooling air at *a* and *b* as also at a uniform, but much lower, temperature than inside the coil; then the temperature drop from the copper to *b* will be the same as through the insulation, thermometer bulb and covering pad to the air at *a*. Obviously if the temperature drops through the insulation and through the pad are equal, then the thermometer bulb will show a midway temperature. This is, of course, assuming that the surface drop to the air, previously referred to, is very small, or that it is included as part of the drop through the pad. Obviously, if the drop through the covering pad is made very much higher than that through the insulation proper, then the thermometer bulb more closely approaches the copper temperature. Thus it is seen that all kinds of results may be obtained, depending upon the relative drops through the pad and through the insulation. In a low voltage machine, with relatively thin insulation, the pad may take most of the drop. With very heavy insulation, the pad may take proportionately less and the thermometer reading departs accordingly from the copper temperature. It might be suggested that a big thick pad of very poor heat conducting material might be used. This apparently would tend toward more ac-

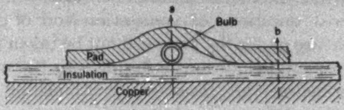

FIG. 4

curate temperature readings, but, on the other hand, harmful effects may be introduced by the use of a large pad. The resistance to heat dissipation being increased in the area covered by the pad, obviously less heat will be carried away at this point and, therefore, the heat generated under the pad must be conducted to adjacent parts of the coil. This means an increased temperature at this point, due to the use of the pad. Again, the use of the pad, in some cases, may affect the normal ventilation of certain parts of the coil not directly covered by the pad. For instance, if there is a ventilating space between two adjacent armature coils, through which air is normally driven, a pad which covers this space even partially may create more or less of an air pocket, and thus materially affect the heat dissipation, and the temperature directly under the pad. Experience has shown that both of the above conditions are obtained when good judgment is not used in the application of the covering pad. This, of course, applies particularly to those cases where temperature readings are obtained while the machine is in operation. Of course, after shut-down, most questions of ventilation and of generation of higher temperature under the pad need not be taken into account.

There are so many conditions entering into the interpretation of the thermometer and resistance methods of determining temperature, that in certain classes of apparatus it has been very desirable to find more accurate methods. One of these is in the use of so called resistance coils. In this method a coil of fine wire of a known temperature co-efficient, and of known resistance at a given temperature, is placed at the spot where the temperature is to be measured, and the temperature rise is determined from the increased resistance of the coil. One serious objection to this arrangement, is that the resistance coil must have considerable length and breadth so that it really indicates the average temperature of a considerable area instead of a point. When placed between two coils, as indicated in Fig. 5, it usually occupies so great a proportion of the slot that it indicates an average temperature considerably lower than at a. Furthermore, on account of the length of such coils, there may be a considerable difference between the temperatures at the two ends. Thus the resistance coil, like the resistance measurement of the windings themselves, gives an average result, but this average may be limited to a comparatively small area, whereas, in the resistance method in general the indicated rise is an average of the whole winding. However, in the resistance method, the temperature of the conductors themselves is measured, whereas, with the resistance coil the temperature measurement is outside the insulation. The resistance coil method is, therefore, a relatively crude approximation, although when brought out it was really an important step in advance. In its early application, many misleading results were obtained, due largely to lack of understanding of the principles governing temperature distribution and temperature drop. In some cases, the resistance coil was placed under the wedge as at *b* in Fig. 5. In other cases, the coil was placed at the side of the slot next to the iron, or at the bottom. Very rarely was it placed midway between the two coils, probably because this was a more difficult application and also because the greater accuracy of such location was not recognized. From the use of resistance coils many good engineers drew the conclusions that the upper limit of permissible temperature for fibrous insulations was only 80 deg. to 90 deg. cent., because with the coils located in certain ways and places, deterioration of insulation at some other point was liable to begin, if the above temperatures were exceeded. The error was in not recognizing the temperature drop between some hotter spot and the average location of the resistance coil. When this condition was recognized, the results obtained by resistance coils became more consistent with the facts.

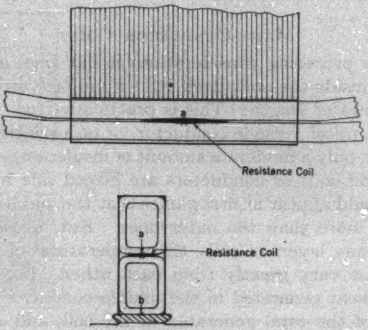

FIG. 5

A later development than the resistance coil is the thermocouple as a practical device for measuring temperature. One great advantage of the thermocouple is its very small size, so that it can indicate the temperature at practically a point instead of a very considerable area. Moreover, as it is a zero current method of measurement, when used with a potentiometer no question of size or length of the connecting leads need come up. The thermo-couple is so small and has so little mass, that it can follow very quickly any temperature changes where it is located. If properly placed it furnishes the most accurate temperature indicator which we now have, as it can be located in all sorts of normally inaccessible places. However, its use is practically limited to stationary apparatus. In rotating apparatus, or rotating parts it can be used only after shut-down, which introduces errors, as already shown.

MANY-CONDUCTOR COILS

In all the preceding considerations it has been assumed that the copper inside the coils itself is at a uniform temperature, in any given unit of length. This is practically true, provided the coil is made up of a single conductor, or of a relatively few conductors with only a moderate amount of insulation between them. When several coils or conductors are placed side by side, as in Fig. 6, it would appear at first glance that the middle coils should heat much more than the outer ones. But, in reality, unless there are many layers of coils, the temperatures of the different coils will not vary greatly from each other. For instance, in Fig. 6, the heat generated in the middle conductor is only one-third that of the total generated in the coil, and yet the two side surfaces through which this heat passes to the adjacent coils aggregate almost as much as the total outside dissipating surface of the whole coil, through which all the lateral heat flow is dissipated. Considering further that the insulation between the middle coil and its neighbors is relatively thin compared with the outside covering, it is obvious that the temperature drop from this coil to the adjacent ones will be comparatively small,—possibly not over ten per cent of the drop through the outside insulation.

However, with a large number of coils side by side, the conditions become cumulatively worse. Here, the drop from the center conductor to the next one, may be small. But the drop from the second conductor to the third is considerably greater due to the heat of two conductors being transmitted. From the third to the fourth there is a drop corresponding to the losses of three conductors, etc. Thus, there is a gradually increasing temperature drop from the center of the coil toward the outside surface, and if the coil be very deep, that is, if it consists of many insulated layers, the sum total of the drops may be quite large. Or, putting it in another way, with a comparatively deep coil the temperature rise from the outside surface of the coil itself toward the center will be very rapid at first, and gradually taper off, as indicated in Fig. 7. This is indicated very clearly in the case of an over-heated field of coil of fine wire. Here the first outside layers will usually be found in a fairly good condition, but at a comparatively little distance inside the coil there may be severe roasting or evidence of overheating, which may be almost as bad as at the center. (See Fig. 8.) In such case, the temperature measurement on the outside of the coil is no satisfactory indication of the hot-spot temperature. A temperature measurement by resistance, while a closer indication than that by thermometer, also may be very misleading. It may be stated that modern design tendencies are toward comparatively shallow field coils, largely on account of this condition.

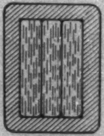

Fig. 6

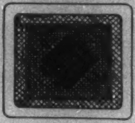

Fig. 8

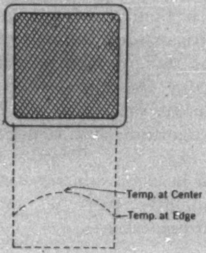

Fig. 7

Conclusion

The whole object of this paper is to show the problem of temperature distribution and temperature measurement, as it actually is. It is the writer's desire to show that no hard and fast rules can be made for determining the facts in the case, and that the best rules and methods now practicable are only approximate. The present limitations set for insulating materials are much higher than were considered practicable only a few years ago. This is not because the limits have been raised, but because, through a better understanding of the facts, the real upper limits of temperature as fixed by durability of insulation, are now known to be considerably higher than was believed to be the case only a short time ago. If the real limits were in accordance with former beliefs, then all the evidence of the more accurate modern tests and data would indicate that the vast majority of the existing electrical machines should have "roasted out" comparatively early in their operation. The higher temperature limits were there, but were not recognized. Now we recognize them and attempt to make reasonable allowances for differences between the measurable temperatures and the actual hottest parts. The present method may be crude, but we are not going at it blindly, as was formerly the case. Formerly the manufacturer took the real responsibility for making a machine that was safe for the service, whatever the guarantees called for. Today the responsibility is still his, but he is attempting to educate the public to a knowledge of his real problems, and to a recognition that temperature determination is far from being an exact art. There is no sharply defined line between *good* and *bad* in the insulating materials as affected by temperature, consequently there is no sharp line between *safe* and *unsafe* temperatures.

Presented at the Chicago Section meeting of the American Institute of Electrical Engineers, November 27, 1916.

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RATIONAL TEMPERATURE GUARANTEES FOR LARGE A-C. GENERATORS

BY F. D. NEWBURY

Abstract of Paper

The paper is an argument for the standardization of temperature guarantees when the guarantee is based on internal temperatures as measured by thermocouples. It is recommended that in all cases the maximum safe operating temperature of the insulation be used as the temperature guarantee, instead of using a lower temperature. The standardized guarantee, 50-deg. rise by thermometer, is cited in comparison with the present wide range of temperature rises, from 60 deg. to 100 deg., that have been called for in specifications when the thermocouple method of measurement is used. Arguments are presented from the stand-point of both the designing and the operating engineer for the use of this standardized temperature rise. Curves are shown illustrating the temperature conditions in both stator and rotor of a typical large, high-voltage turbo-generator. Examples, based on these curves, are given to show that a low temperature rise guarantee for the stator does not necessarily result in margin for overloads. This margin for overloads is the main argument that can be advanced in favor of low temperature rises. The only way in which the purchaser can be certain of overload margin is to have the specifications call for the maximum rating desired, in which case the maximum safe operating temperature may logically be made the temperature guarantee.

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OPERATING engineers are familiar with the use of a single standardized guarantee of temperature rise by thermometer for large single-rated generators, and particularly for turbo-generators. During the past five or ten years, such generators have been purchased very generally on the basis of a 50 deg. rise, measured by thermometer. This standard rise was fixed at 50 deg. because it was felt, by reason of general experience, that this represented the maximum safe rise. It was recognized that with guarantees based on the temperatures of external surfaces, a single limit could not be fixed that would fit all cases; yet a single limit was fixed and has been adhered to in practically all commercial transactions. This standardized guarantee, moreover, takes no cognizance of the inherent variations in the actual temperature performance of individual units. A high-voltage generator and a similar low-voltage generator under some conditions should be designed for quite different temperatures as measured by thermometer (on account of greater temperature drop due to thicker insulation with high voltage) yet both these units would be guaranteed for a rise of 50 deg. in accordance with this established practise.

In the commercial introduction of the thermocouple or resistance-coil methods of measurement, as a basis for guarantees there has been a tendency to lose sight of this idea of a standardized guarantee. When this method first appeared in contracts about three years ago, guarantees for "hot-spot" rises as low as 40 deg. were required in some instances. As the real significance of the results obtained by these internal measurements became better known, the specified temperature rises based on this method have gradually increased up to the relatively high values consistent with the safe operating temperatures of mica insulation. With built-up mica insulation, a safe operating temperature of 150 deg. may be guaranteed, and the corresponding temperature rise guarantee may be 105 deg., or, in round numbers, 100 deg. Yet even today there is no uniformity in guarantees. Temperature rises of 60 deg. are often called for in specifications, even when mica insulation is employed, and practically all temperatures between 60 deg and 100 deg. have been used as guarantees on one occasion or another.

In discussing maximum permissible rises, the author has in mind the limits allowed when mica or other Class B insulations are used. The maximum safe rise allowed by Class A insulations is only 60 deg. and this is so near the familiar guarantee of 50 deg. rise by thermometer that there is no tendency to give guarantees below the possible maximum when this class of insulation is employed.

From the standpoint of the designer of large generators, the desirability of a standardized temperature guarantee that is consistent with the safe operating temperature of mica insulation is apparent. When other conditions permit, full advantage can be taken of the heat-resisting properties of the insulation and the most efficient and economical design can be produced. In the largest two- and four-pole generators, it is not only desirable, but in many cases it is necessary that such advantage be taken in order that the safest mechanical design may be produced. It is good common sense that the copper and the sheet steel cores be pushed to the limit, electrically and magnetically, so that greater factors of safety may be provided in the all-important mechanical features of the design. There are so many real limitations imposed by the physical characteristics of the available materials that demand careful consideration in the design of high-speed machinery, that the imposition of additional "man-made" restrictions should by all means be avoided. They only serve to uselessly impede progress.

In a fair, sensible contract there should be no conflicting or inconsistent guarantees. It is now customary to include in many contracts for large generators a guarantee covering the total temperature that the insulation will continuously withstand without injury. Such a guarantee of the insulation is virtually a guarantee of maximum capacity—so far as capacity is determined by heating—and so covers, broadly, the same ground as the guarantee of temperature rise. Obviously, the two guarantees should be equivalent. An example will make this clear. With suitable mica insulation, 150 deg. is frequently used as the safe limiting temperature guarantee. Assume that this guarantee is made and also that the generator is guaranteed to deliver its rated kilovolt-amperes without exceeding a temperature rise of 80 deg. Two different guarantees will have been made; one that the generator will deliver its guaranteed load with a total existing temperature of 125 deg. (adding 40 deg. air temperature and 5 deg. allowance to the guaranteed rise in accordance with the A. I. E. E. Standardization Rules); and another that the generator can be safely operated up to a temperature of 150 deg. The guaranteed temperature rise should have been 105 deg. to make the two guarantees consistent and rational.

In considering the subject of low versus high temperature rise guarantees, one is apt to look upon a low rise in itself as an advantage just as low loss in a generator is an advantage. A temperature rise guarantee, however, is radically different in nature from a loss or efficiency guarantee. In the case of efficiency the operator is interested in what the apparatus will actually do; any reduction in losses is of direct benefit, and the greater the reduction, the better will be the generator. With temperature, on the other hand, the operator is only interested in temperature rise to the extent of knowing that it is safe; he is not primarily interested in temperature figures. If the operating temperature is safe, a lower temperature will be no safer and of no particular value.

The importance to the operator of a temperature guarantee lower than that permitted by the characteristics of the materials is frequently over-estimated. It is felt, naturally enough, that this margin permits the generator to safely carry heavier loads than contracted for or to safely operate under abnormal conditions in emergency. The fact that the value of the guaranteed safe limiting temperature is based on continuous service gives sufficient margin for emergencies. For limited periods—and this can safely amount to months of service in the aggregate—considerably higher temperatures are permissible, and this margin will cover any probable combination of emergencies. A completely mica-insulated generator has seldom, if ever, failed on account of insulation breakdown due to excessive loading in emergency. The limiting load is usually reached because of some other factor, such as turbine capacity, ability to maintain voltage, etc.

It may still be argued that a low stator rise is desirable on account of the margin it gives for continuous overloads. There would be a better basis for this argument if an equal margin were provided in the design of the generator in all other respects—in rotor heating and exciting voltage particularly. But this is seldom, if ever, done. While practise in stator temperature rise guarantees is still somewhat unsettled, the practise in rotor temperature rise guarantees is pretty well fixed. For the generators under consideration, a rotor rise in the neighborhood of 100 deg. by resistance at the maximum rating is well established. Thus, even if a rise as low as 60 deg. be guaranteed for the stator, a rise of 100 deg. is often given for the rotor of the same generator. This at once makes it impracticable to take advantage of the assumed reserve capacity of the stator. Any increase in load, resulting in an increase in the temperature of the armature winding will cause a much greater increase in field winding temperature and voltage drop with this initial field temperature. Consequently, if an overload is contemplated, the temperature rise of the field winding at the nominal load should be approximately the same as that of the armature winding.

Some fundamental relations in large turbo generators are illustrated by the Curves, Figs. 1, 2, and 3. These curves will be used to explain, among other things, the above statement. Fig. 1 shows the variation of armature temperature rise with changes in load on the basis of 100 deg. rise at 100 per cent load. The rises in different parts of the stator are shown by the several curves. These curves are based on careful factory tests of various generators, approximating 20,000 kv-a., at 1800 rev. per min. and 13,000 volts. They may be considered as typical of the large, high-speed, high-voltage generator. Temperature tests were made at normal voltage and open circuit and at normal voltage and at various percentages of rated load. The temperatures at other than tested loads are taken as proportional to the losses involved. In the case of the cooling air, the temperature rise varies in proportion to the total losses of the generator; in the core, the temperature drop varies with the total stator losses (neglecting the relatively small loss dissipated through the coil ends); and in the case of the winding, the temperature drop through the insulation varies with the total loss in the embedded copper. These curves are only roughly approximate but are sufficiently accurate for the present purpose. They give a picture of the temperature conditions in the stator of many of the large high-voltage turbo-generators that have been placed in operation during the past three years.

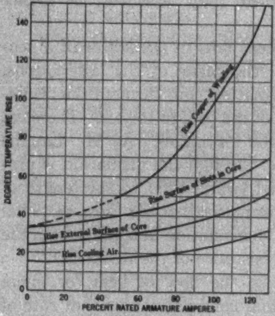

FIG. 1—TEMPERATURE CONDITIONS IN LARGE TURBO-GENERATOR STATORS

According to these curves, in such a turbo generator, at 100 per cent of rated load, the cooling air rises 25 deg.; the outside surface of the core rises 40 deg. above the entering air, or 15 deg. above the temperature of the discharge air in contact with this surface. There is a drop of 45 deg. through the armature coil insulation, giving the total rise of 100 deg. in the copper. It will be noted that nearly half of this total rise is accounted for by the temperature drop through the insulation and consequently, any material reduction in the total rise must involve a substantial reduction in the temperature drop through the insulation. In considering these curves it must be borne in mind that they represent the average generator of a particular class and are based on generators designed to operate at 100 deg. rise in the stator copper at rated load.

On account of its importance, it is well, at this point to consider in detail the reasons for this relatively large temperature drop through the coil insulation and the factors that determine it. The temperature drop through the insulation is probably the most important single item in determining the copper temperature and is directly responsible for the greater part of the difference between temperature measured by mercury thermometers placed outside of the insulation on the coil ends and by thermocouples placed so as to approximately measure the true copper temperature.

The general principles on which differences between internal and external temperatures depend have been explained in the paper by Mr. Lamme, on *Temperature Distribution in Electrical Machinery*, and need not be given here. The particular points that apply to the present problem may, however, be briefly stated.

The most important path of heat flow in the stator of a generator having a long core is in the plane of the laminations, that is, from the copper of an armature coil, through the insulation, and through the sheet steel of the core to the air. The most important part of this path is the insulation. As Mr. Lamme points out, the temperature drop through the insulation is proportional to the heat transmitted (watts loss) to the length of the path (the thickness of the insulation) to the cross sectional area of the path (the surface of the insulation in contact with the core laminations) and the heat resistance of the material.

A measure of the resistance to the flow of heat, or, more properly, a measure of the thermal conductivity, is that rate of heat flow, expressed in watts, that will cause a drop of one deg. cent. when transmitted through an inch length and a square inch section of the material; just as in the electric circuit the conductivity might be expressed as the value of current flow that will cause one volt drop through an inch cube of the material. Values of thermal conductivity of composite forms of insulation are difficult to determine because different samples, apparently similar, give widely differing results. This is largely due to the effect of air pockets in the insulation. The tighter the insulation, the higher will be the conductivity. For example, in tests made by Symonds and Walker*, solid mica was found to have a thermal conductivity of 0.00915 watts per inch cube, while built up mica coil insulation had a conductivity less than one-third of this. Glass (to consider another solid ordinarily

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*"Heat Paths in Electrical Machinery", Harold D. Symonds and Miles Walker, *Journal I. E. E.*, Vol. XLVIII, 1912, p. 674.

thought of as a poor heat conductor) is about ten times as good a conductor as the usual coil insulations. It is safe to say that the degree to which air spaces exist in the insulation has more influence on the heat conductivity than does any difference there may be in the conductivities of the various component materials such as paper, cloth, varnish, mica, etc., From the best data available it appears that the heat conductivity of coil insulations, commonly used, varies from 0.0025 to 0.005 watts per inch cube of the material; the lower range of figures applies to the older hand-wrapped materials while the higher range covers insulation applied under heat and heavy pressure by machinery. From the standpoint of heat conductivity and temperature drop the importance of tightly wrapped, compact insulation is obviously very great.

When the rate of heat flow, expressed in watts, and the thermal conductivity and dimensions of the insulation are known it is possible to calculate the temperature drop through the insulation with a fair degree of accuracy. The determination of the rate of heat flow, however, involves two factors that require considerable experience to estimate; one, the proportions of the total heat that are transmitted along the copper to the coil ends and through the insulation to the core; and, the other, the increase in loss due to eddy currents in the copper.* Since the present purpose is only to show the order of magnitude of this drop and the reasonableness of the figure given for the typical generator in Fig. 1, it will be sufficiently accurate to assume that one factor offsets the other; that the eddy current losses are equal to the loss transmitted longitudinally through the copper. It will also be assumed that the insulation is as compact as it is possible to make it and has a thermal conductivity (including the air space† between the coil and slot) of 0.0035 watts. It is usual in units of this class to work the copper in the neighborhood of 1600 amperes per sq. in. which results with slots of usual proportions, in a loss (considering only I^2R loss at the operating temperature as previously explained) of 0.6 watts per square inch of insulation surface. For 11,000 or 13,200 volts, a reasonable thickness of insulation from copper to core may be taken at 0.25 inch. Using these figures the temperature drop may be calculated thus:

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*It is interesting to note that the eddy current loss in the copper, in a well designed generator is only a small part of the load loss measured with the generator short-circuited, and that there is no method, so far as the writer knows, of accurately calculating this loss. The theory and formula developed by Field, Rogowski and others only cover the limiting cases of solid conductors or infinitely laminated conductors.

†Still air has a thermal conductivity only one-tenth that of built up insulations. Even with the closest possible fit between the coil and the laminations, which present a more or less rough surface to the coil, there is an appreciable decrease in the conductivity due to this "joint."

Thermal drop (in deg. cent).

$$= \frac{\text{Watts} \times \text{thickness of insulation (inches)}}{\text{Surface of insulation (sq. in.)} \times \text{thermal conductivity}}$$

or:

$$\text{Thermal drop} = \frac{0.6 \times 0.25}{0.0035} = 43 \text{ deg. cent.}$$

This checks with the 45 deg. used in the typical curve.

It is apparent that this drop can be reduced by decreasing the watts per sq. in. (by decreasing the current density or increasing the slot surface or by both) by decreasing the thickness of the insulation or by improving its thermal conductivity. With existing insulating materials and methods it is not feasible to materially reduce this temperature drop by these latter methods. Neither can the slot surface be materially increased nor the current density be reduced except by correspondingly increasing the dimensions of the stator, and this may be undesirable or even impracticable in the largest two- and four-pole generators on account of mechanical limitations.

The thickness of the insulation and therefore the thermal drop is a direct function of the rated voltage. At 2400 volts for example, the thickness of insulation and the drop are roughly half the corresponding figures for 11,000 volts. While it is generally recognized that the internal temperatures in high-voltage generators are greater than in low-voltage generators for equal surface temperatures, it is, perhaps, not so generally appreciated that the temperature drop varies so directly with the thickness of insulation and amounts to such a large figure.

This question of temperature drop through the insulation has been considered somewhat in length because it is the most important single factor in determining the hot-spot temperature in large high-voltage, high-speed generators. If the magnitude of the temperature drop through the insulation is recognized, the difference between a 50 deg. guarantee by thermometer and a 100 deg. guarantee by a properly placed thermocouple is immediately explained. It will be noted that in the typical generator, illustrated by Fig. 1, the temperature rise of the core surface is only 40 deg. and the temperature rise of the exposed end windings would be in the neighborhood of 50 deg. using ordinary methods of applying thermometers. In other words, this generator which has a hot-spot temperature rise of 100 deg. would probably meet a 50 deg. rise guarantee based on surface temperatures.

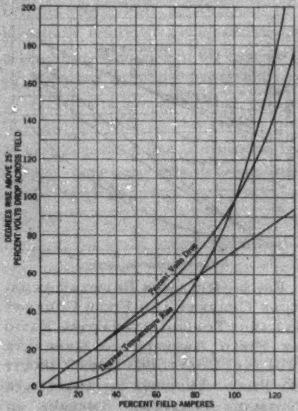

Fig. 2—Temperature Rise and Volts Drop in Large Turbo-Generator Rotors

Fig. 2 shows the increase in field temperature and voltage drop with increase in field current. The temperature curve is based on the assumption that the temperature rise at rated load is 100 deg. and is proportional to the loss at other loads. The loss and temperature rise increase considerably faster than in proportion to the square of the current, due to the increase in resistance with temperature. This factor becomes of very great importance at the relatively high temperatures at which turbo fields are ordinarily worked. Thus, with a 10 per cent increase in field current, above 100 per cent of rated current, the temperature rise increases 33 per cent, where only 21 per cent would have resulted if the resistance had remained constant. Due to this effect and also to the second-power relation between the current and loss, the temperature rise increases at a greatly accelerated rate for current above normal. For example; the first 100 deg. of rise is produced by 100 per cent of normal full-load field amperes; the second 100 deg. rise is produced by an additional 25 per cent of normal amperes; and the third 100 deg. of rise is produced by only 15 per cent of normal amperes. In other words, to obtain an increase of 40 per cent in ampere turns, the loss must be tripled and the temperature rise must be increased from 100 deg. to 300 deg. There is also a correspondingly rapid increase in required exciting voltage for field currents above normal. Even though the drop increases only in proportion to the first power of the current, the further increase due to the increase in resistance makes the total rate nearly as great as in the case of the loss and temperature rise. The drop on the basis of constant resistance is shown by the straight line in Fig. 2. The difference in the ordinate of this straight line and the total drop shows graphically the large effect of the change in resistance at currents above normal. To obtain only 25 per cent increase in exciting ampere-turns, an increase of 60 per cent in exciting voltage is demanded. This increase in exciting voltage is, in the majority of mica insulated generators, the real limit to overload capacity. The insulation used in the rotors of large turbo-generators with which the author is familiar is solid molded mica between the copper and ground, and mica and asbestos tape between turns. Such insulation can obviously withstand temperatures of several hundred degrees, yet the total temperature is limited to 150 degrees, on account of the prohibitive increase in exciting voltage, just described, that occurs with higher temperatures. Thus, so far as the rotor is concerned, temperature is not directly a limit to capacity.

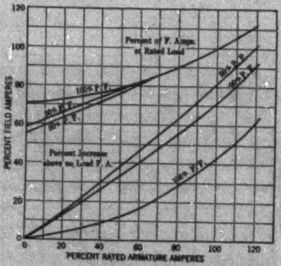

FIG. 3—RELATION BETWEEN ARMATURE CURRENT AND FIELD CURRENT IN LARGE TURBO-GENERATORS. RATIO OF FIELD AMPERES TO GENERATE NORMAL VOLTS ON OPEN CIRCUIT TO FIELD AMPERES TO CIRCULATE NORMAL ARMATURE AMPERES ON SHORT CIRCUIT EQUALLING 1.00

Fig. 3 shows the relation between armature amperes and field amperes in a large turbo-generator of average design proportions, and ties together the data given in Figs. 1 and 2. While differences between individual units will change this relation to some extent, the change will not be of such magnitude as to affect the conclusions reached. The three lower curves show the *increase in field current above the no-load value* for different power factors. In the upper curves these same data have been expressed as the *percentage of the full-load field amperes* at each of the three power factors. These curves show that in three different generators, one designed for 100 per cent power factor operation, a second for 90 per cent power factor, and the third for 80 per cent power factor, all having the same ratio between armature and field strengths, the increase in field current expressed as a percentage of full-load field current will be the same between 70 per cent and 120 per cent of rated load. For the present purpose, operating power factor may therefore be disregarded, *providing the generator is assumed to operate at the power factor for which it was designed.*

These curves may now be used to prove the statement, previously made, that, in order to provide additional capacity in a generator beyond the contract rating, it is necessary that the temperature rise guarantees of the armature winding and of the field winding be approximately equal. If a generator has a true hot-spot rise of 60 deg. in the stator and a rise by resistance of 100 deg. on the rotor the promise of margin for overloads given by the low armature temperature will prove to be fruitless. To restate this in the words of the original proposition; a low stator rise does not guarantee margin for overloads.

The question will be considered in two ways; first, to show what field winding temperature rise and exciting voltage are consistent with an armature temperature rise of 60 deg.; and second, to show what field winding temperature rise and exciting voltage will result when the load is increased so as to increase a low armature temperature rise to the safe operating temperature with a generator having an initial field temperature rise of 100 deg.

Let it be assumed that a purchaser believes more margin in stator temperature rise is desirable in order to obtain margin in capacity for contingencies, and specifies that the stator temperature rise as measured by thermocouple shall not exceed 60 deg. What rotor temperature rise and what margin in exciting voltage should be specified in order that this expected margin may be realized? This condition requires that a consistently designed generator be assumed; that is, a generator capable of operating at the anticipated maximum load within the guaranteed safe limiting temperature of the insulation in both armature and field, and requiring an exciting voltage within that available, or, in other words, a generator having characteristics shown in Figs. 1, 2, and 3, at the maximum expected rating. This generator, as illustrated by Fig. 1, must be derated from 100 per cent to 66 per cent rating to meet 60 deg. rise in the stator, so that a high-voltage generator, of these relative core and copper temperatures, that meets 60 deg. rise at its nameplate rating, can carry 50 per cent overload continuously, and still operate within the safe temperature of mica insulation. The relative core and copper temperatures may be varied somewhat in different designs, but on account of the magnitude of the core loss and windage loss, as compared with the stator copper loss, the feasible variation is not large.

From Fig. 3, 66 per cent of rated armature amperes requires 84 per cent of the field excitation at 100 per cent load. From Fig. 2, the temperature and exciting voltage at 84 per cent field excitation are 64 deg. and 76 per cent respectively. Thus, consistent guarantees would be 60 deg. by thermocouple, for the armature, and 60 deg. by resistance for the field winding, and the generator should be designed to require not more than 90 volts exciting voltage (on the basis of 125 volts available). In taking the required field current at the nameplate rating from 66 per cent rating on Fig. 3, we have, in effect, maintained the assumed unity relation between armature and field strengths at the capacity rating. This results in a ratio of 1.5 at the nameplate rating, which is a higher ratio than would probably be used for a large two- or four-pole turbo-generator. In other words, in an actual design, the field would be relatively weaker than in the above case, and the increase in field current, temperature, and exciting voltage, would be greater than in the example and the guaranteed figures for the rotor should be correspondingly lowered. To complete the story, then, this ratio or an equivalent design figure, must also be specified.

The determination of consistent guarantees that will make certain a desired margin in generator capacity, no doubt appears, from this example, to be a complicated matter. It is, if the purchaser attempts to secure margin in capacity in this indirect fashion. If this margin is really desired, the purchaser should make the desired maximum rating and the contract rating the same, when all these difficulties will disappear. The low temperature rises will, incidently, also disappear from the contract.

To illustrate the second form of this question, assume that a generator has been purchased on the basis of a stator rise of 60 deg. by thermocouple and a rotor rise of 100 deg. by resistance. It is assumed that both armature and field are mica-insulated. Thus there is a margin in capacity in the armature equal to 50 per cent of its rating, while there is no margin, on the basis of the guarantees, in the field. If the load were increased to the limit of the armature, there would result a temperature rise in the neighborhood of 400 deg. in the field, and an exciting voltage would be required nearly three times normal. Of course, these are impossible operating conditions;— with these assumed rises of 60 deg. and 100 deg. there is no possibility of taking advantage of the low armature temperature. Consider then a less extreme case. Let the armature rise be 80 deg. when the field rise is 100 deg. Then an increase in load of 14 per cent (from 86 per cent to 100 per cent, Fig. 1) is permissible, without exceeding the limiting safe rise of 100 deg. This requires an increase of 9 per cent in field excitation (Fig. 3); and results in a rise of 130 deg. and a voltage drop across the field winding of 117 per cent. This would require an exciter voltage of approximately 150 volts on the basis of 125 volt excitation.

These examples illustrate the point already made, that a low temperature rise guarantee for the armature is not in itself a guarantee of operating margin; that the only way in which this margin can be surely obtained is for the purchaser to draw his specifications for the maximum rating desired. Obviously, at this maximum rating the maximum safe temperature rise may be used.

After all is said, the demand for low temperature guarantees usually has back of it a skepticism as to the real safety of the limiting temperature claimed for the insulating materials. Operating engineers may safely leave this question with the designers. In this particular field of design, assumed limits are being continually exceeded and extended. New designs are, from necessity, based on an experimental study of materials and on an analysis of constructions and of complex phenomena involved in the operation of the generator to a greater extent than on direct experience with similar machines. On no other basis could sizes of high-speed units have been increased in single steps from 10,000 kv-a. to 20,000 kv-a. or from 35,000 kv-a. to 50,000 kv-a. Under these conditions, the guarantees made in the contract are really of secondary importance as compared with the ability and experience of the designers. The situation is quite different from that existing with smaller medium-speed machines where the temperature and other guarantees are, in many cases, the operators's principal safeguard. With these large turbine units, each one representing an investment of several hundred thousand dollars, the designer must be conservative; chances cannot knowingly be taken. Whether the temperature rise guarantee is 100 deg. or 50 deg., or, if in the future it should become 150 deg., the engineering public may rest assured that, everything considered, it is conservative. Those responsible for the fulfillment of contracts cannot afford to have it otherwise.

DISCUSSION ON "TEMPERATURE DISTRIBUTION IN ELECTRICAL MACHINERY" (LAMME), "RATIONAL TEMPERATURE GUARANTEES FOR LARGE A-C. GENERATORS" (NEWBURY), CHICAGO, ILL., NOVEMBER 27, 1916.

Alexander Gray: Mr. Lamme has pointed out the difficulty experienced in making and in interpreting temperature measurements, and has suggested that the expert designer can predict hot-spot temperatures more closely than they can be measured. Mr. Newbury in addition has pointed out the absurdity of the low temperature guarantee sometimes demanded on large generators, with the idea that a large overload capacity may thereby be obtained, when such overload capacity is not available because of some limitation other than heating.

Most engineers are now satisfied that 150 deg. cent. is a safe operating temperature for mica insulation and Mr. Newbury, in support of a plea that designers and manufacturers of large machines be not restricted to lower temperatures, brings out the following points:

(a) The higher the permissible temperature the smaller the machine for a given output and the safer it is mechanically.

(b) Generators completely insulated with mica have seldom failed on account of insulation breakdown due to emergency overloads.

(c) The limiting load is generally fixed by turbine capacity, by ability to maintain voltage, or by some cause other than heating.

(d) The overload margin provided by a low stator temperature is not available because of rotor heating and because the exciting voltage is limited.

(e) The customer should secure the desired margin of capacity by making the desired maximum rating and the contract rating, one and the same thing.

(f) With large turbine units representing an investment of several hundred thousand dollars the designer will not take chances.

These statements are not all free from criticism. It is true that the use of high temperatures has allowed the use of smaller and safer machines for a given output, but it has also allowed the original machine to be rated up without any increase in safety. Furthermore, it does not seem reasonable that exciting voltage should necessarily be a limitation in such machines. The point of the whole matter is rather that the designers are willing to bet several hundred thousand dollars of the manufacturers money that 150 deg. cent. is a safe temperature for large generators properly insulated, but the operating engineers are still doubtful.

Just as the older generation of steam engineers had to be weaned away from the reciprocating engine, so the electrical engineer, accustomed to associate low temperature with safety, will have to be educated to the use of higher temperatures. The operating engineer feels that there is an essential difference between the stator and the rotor guarantee, because the rotor voltage is low with seldom more than one volt between turns, while the stator voltage may be 13,200 volts with 100 volts between turns. If any one of these stator coils is loosely wrapped a hot coil will result, also it is possible that tightly wrapped insulation will become loose due to vibration and to the gradual disintegration of the binding varnishes. Is it then surprising that, of two machines offered, alike in price and in operating characteristics, the purchaser will select the one with the lower stator temperature guarantee because, even although the margin of safety is not available in additional output, it is available in that it gives an additional sense of security?

For my own part I have great faith in mica insulation, and I agree with Mr. Newbury that all parts of the machine should be run as hard as they will stand. Most engineers, however, are not constantly in touch with new designs, new insulating materials, and a great mass of test data, and so they are more conservative than the designer who has such data at his disposal.

W. J. Foster: It is, indeed, surprising that more attention was not given to the laws governing heat flow by the earlier designers of electric machines when we consider how well these laws had been formulated by physicists many years before much attention had been given to electricity. Many of our physical laboratories—not only those of the universities and colleges but of our secondary schools—did considerable experimental work in connection with temperature distribution before any electrical engineering school was established.

The ideal heat remover is water, by reason of its great capacity for heat, but such difficult problems are involved in making use of water for rotating machinery and the risks of serious damage, due to accidents, are so great that very little use has been made of water in the cooling of electric machines. Circulating air is almost the sole agent for heat removal. The problem then resolves itself into the proper control of the air flow. It is evident that the more rapid the speed of the air on any surface, the more heat that can be removed, and also that it is of great importance that that circulating air be conducted to all surfaces exposed to the air and that none of the air be allowed to return. It is extremely difficult in certain types of machines to prevent the eddying of the circulating air and considerable skill is required in designing so as to prevent eddies. As intimated by Mr. Lamme, a designer can now predict very closely—by taking into consideration the quantity of heat generated in the several parts, the paths for flow, the consequent rate of flow and the heat resistance of the various materials in the paths—the internal temperatures in any given type of machine. Perhaps the most important factor in his equation is the quantity of heat generated in any given case. The source of heat he knows fairly well, with the possible exception of the eddy currents. There is no doubt that the greatest element of uncertainty in the prediction of temperatures is the eddy currents. Hence, it is of great importance for the designer to have methods of predetermining eddy currents in much the same manner as he predetermines the strength of the metals used in the mechanical parts of the machine by measurements in the mechanical laboratory. Static impedance methods have been developed for the measurement of eddy currents that are found in practise to be quite reliable. Hence, it is inexcusable for the modern designer to make a serious blunder in the ordinary electric machine. This statement does not apply to radically new machines or those where great risks in eddy currents must be taken by reason of the extreme difficulty of obtaining a safe mechanical structure.

In connection with the diagram shown by Mr. Lamme to illustrate temperature drop through the various media that are interposed between the copper of the winding and external circulating air, it is interesting to note that the allowances over and above determined temperatures for the "hot spot" as now standardized in the A. I. E. E. are quite wide of the mark. If through any media we have a temperature drop of 20 deg. cent. at a certain heat flow, it is obvious that with double the heat flow the drop will be doubled. Let us assume that any measuring device—like a thermocouple or temperature coil—will be a few degees removed from the hot spot. If with a certain heat flow it is 5 deg. removed, with double flow it will be 10 deg. removed. Consequently, when the load is so adjusted that the temperature rise as measured by this device is 100 deg. above room temperature, the allowance over and above for the hot spot should be twice what it is when the indication is 50 deg. cent. rise above room.

Referring to Mr. Newbury's plea for the use of higher temperatures in contracts in mica insulated windings and his discussion of the safe temperature of different materials, I question whether the line of demarcation between safe and unsafe can be absolutely drawn for any insulation that is built up and more or less composite in its nature, as is practically all insulation on the windings of electric machines. With more margin of safety, longer life will result. This fact, more than the expectation of possible overloads, is undoubtedly responsible for some operating companies specifying the 60 deg. rise, and at the same time asking for a guarantee of a safe operating temperature which is higher than they ever expect to obtain. Often the insistence upon temperature rise in the stator not exceeding 60 deg. when 85 deg. or 100 deg. is permitted in the rotor, results in a machine of higher efficiency, as the reduced copper losses more than offset the increased iron losses in the deeper teeth. It should be remembered that higher temperatures exist in the rotor than in the stator from the nature of the machine. In the largest and highest speed turbo-generators there is a limit to the space that can be given up to the copper and to the weight that can be carried, whereas such limitations do not exist in the stator.

In connection with Mr. Newbury's paper, I am inclined to think that there is some danger of the impression becoming established that no electric machine is safe that does not have high temperature insulation. I think this will be just as unfortunate as to have the impression abroad that the rotor parts of a small low-speed engine-driven dynamo should be constructed of the strongest material, such as nickel steel or just the same as used in the largest and highest-speed steam-turbine-driven dynamo. It is a well known fact that the lower temperature insulations known as "Class A" in the A. I. E. E. Standardization Rules are superior in certain characteristics to the high temperature known as "Class B." Therefore, such insulation should be used where the conditions of service are such as to produce low temperatures under all conditions of operation.

C. J. Fechheimer: Since the time that so-called temperature detecting devices (including resistance coils and thermocouples) have been employed for the purpose of determining the maximum temperature of the stator windings in large a-c. dynamo electric machinery, the purchasing public has been to a large extent of the opinion that such devices were the means of determining with considerable accuracy the temperature of the hot spot in the stator. Especially have they been of this opinion when the temperature measuring device was placed between the upper and lower coils, when the usual lap or wave windings were employed. Our knowledge of the subject of temperature measurement is now slightly greater than it was at the time the hot-spot question was under considerable discussion, and we now know that unless all the facts pertaining to the case in question are known, the temperature detecting device may give indications which are considerably in error. Mr. Lamme has pointed out certain sources of error, and we wish to call attention to a number of others.

If the device is placed between the coil and the iron as, for example, at the bottom of the slot, the reading will be nearly an indication of the iron temperature and does not allow at all for the thermal drop from the copper to the iron. Therefore, the correction given in the Institute Rules for devices placed in this manner is, in our opinion, worse than an estimate or approximation. Even though such temperature indicating device at the bottom of the slot, plus a correction, were near the copper temperature for that particular part of the coil, it might be far from registering the temperature of the copper in part or in the whole of the upper coil (or upper part of the one coil, if there be but one per slot) as indicated so well in Mr. Newbury's paper of about a year ago.*

Unless coils are very well laminated, the loss in the upper coil may be considerably greater than in the lower coil, especially when there is a large depth of copper in the slot. A temperature device placed between coils can then read only an approximate average of the temperatures of the lower part of the upper coil and the upper part of the lower coil. This is borne out pretty well in Mr. Newbury's paper referred to above. For example, at 1000 amperes, the temperature between core and bottom bar is found to be 92 deg., between bars 170 deg., whereas the bottom bar was found to be at 140 deg., and the top at 210 deg.

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*Trans, A. I. E. E. 1915, Vol. XXXIV, Part II p. 2747.

When heat flows conductively, a certain amount of time is required for the transfer of heat from one place to another; therefore a certain amount of time is required for the temperature device to assume the same temperature as that of the copper in the coil when insulation is interposed between the copper and the temperature device. Hence, when the temperature device is placed between the upper and lower coils, and the machine has not reached constant temperature, the temperature device reading must lag behind the true temperature of the copper. Especially for short-time overloads, will the temperature indication of the device placed between upper and lower coils be liable to considerable error. It is also probable that resistance coils would be slightly more in error than thermocouples owing to the fact that it would require slightly more time for the entire resistance coil to assume the temperature of the surrounding medium than it would for the thermocouple.

It is also probable that with a spacer placed between the upper and lower coils, the indication of the temperature device would be slightly more in error than were such spacer omitted, owing to the fact that heat in that case, will flow from between coils to the laminations, thus tending to produce the same effect as pointed out by Mr. Lamme under, "Errors in Temperature Measurement."

We are calling attention to these errors in measurement, as enumerated above, for the purpose of indicating the futility of the customer relying upon the indications as recorded by such devices, and furthermore upon relying to any great extent upon the temperature guarantees embodied in the contract. We are familiar with other errors in measurement which we have not mentioned, but we believe that those cited should be sufficient to prove our point.

Referring now more specifically to Mr. Lamme's paper, it is interesting to note that whereas heat and electrical insulators obey the same general laws insofar as a comparison of insulating and conducting materials is concerned, the laws no longer hold in all cases for insulating materials only. For example, air is one of the best heat insulating materials known and yet it is by no means the best electrical insulator. Mica will withstand several times the dielectric stress that air will, but air is a considerably better insulator for heat than is mica.

V. M. Montsinger Since electrical apparatus of today is being rated at its maximum capacity, the question of temperature distribution has become a very important factor not only in rotating but also in stationary machinery. As an addition to these two papers which consider, primarily, motors, generators, turbines, etc., I should like to say a few words, in regard to the conditions existing in stationary apparatus, that is, in transformers.

It is, of course, recognized that from a thermal standpoint the conditions existing in transformers are not as complicated as in rotating machinery, for the reason that the copper windings and iron core are not in such intimate relations with each other, that is, there is practically no transverse flow of heat between them, as we have in moving machinery. For this reason we are able to calculate more accurately the internal temperatures of transformers. However simple it appears to be, it really is not so simple and the fact remains that the maximum temperature may in some cases be considerably higher than the average temperature as observed by change in resistance. In making guarantees by average temperature, certain corrections or additions are made for hot spots. Although this is an advancement over the old method of not recognizing that there were any hot spots, the present method must still be recognized as an approximation.

Some of the reasons why the present method of allowing a standard correction to take care of the maximum temperature is not an exact method of getting at the real conditions, are as follows:

1. It is impossible to observe the average temperature at the instant of shutdown, consequently there is always a cooling off of the windings between the time of shutdown and the time of observing the resistance. A correction, therefore, has to be made and it is not always possible to be absolutely accurate in making this correction. It may be stated, by way of parenthesis, that a careful study of this question has been made and the writer hopes, in the near future, to present the results of this before the Institute.

2. No two transformers unless of the same design have the same difference between their maximum and minimum temperatures. For example, if the coils are in a vertical position the upper portion is necessarily operating at a higher temperature than is the lower portion. The same is true if the coils are in a horizontal position, except that here the temperature of the top coil is higher than is the temperature of the bottom coil. This difference between maximum and minimum becomes more marked as the height of coil or coil stack increases.

3. Transformer coils necessarily have to be braced for mechanical reasons and in doing this a certain portion of the coil surface is covered. By properly arranging this bracing, however, the effect of overheating due to this may not be objectionable for ordinary normal load operation.

Considering then the many types or different designs of transformers, each of which has a different temperature gradient, it seems that there is room for improvement over the present method of making guarantees by average temperature.

Mr. Newbury advocates that temperature guarantees, for rotating machinery, be based upon a safe maximum temperature, as determined by thermocouples rather than upon a certain temperature rise observed by thermometers. It seems that the position he has taken is a most logical one and should be applied wherever possible to all types of electrical machinery.

For oil-immersed transformers, thermometers cannot be employed for exploring the temperature of the coils. For this reason guarantees are now based upon average temperatures. While the difference between the average temperature and the maximum temperature of an oil-immersed transformer may not be as great as the difference between the highest observable temperature by thermometer, and the hottest-spot temperature observed by thermocouple in moving machinery, yet it seems that the problems of the two types of machinery are somewhat analogous. Unfortunately the thermocouple is not as suitable for transformers as for generators, etc., because of the potential danger and in order to have a satisfactory temperature indicator for transformers it will be necessary to use some other scheme. Assuming that we had a satisfactory temperature indicator for transformers, it would be interesting to know how operating engineers feel about the practical side of observing the temperature by an indicator as compared with the present method of observing the maximum oil temperature by either indicating or alarm thermometers immersed in oil.

P. Junkersfeld: Some local experiences had a little to do with stirring up this subject about ten or eleven years ago. I refer to the first few years in which we operated turbine-driven generators. Previous to that the engine-driven generators did not present any great difficulties because the surfaces were large, but with the turbine-driven generators a considerable amount of heat had to be dissipated in a small space. That brought up a good many new problems at once, and particularly the problems of insulation and ventilation.

I think it was early in 1907, or nearly ten years ago, when we were fairly certain that these generators were running much hotter than we originally expected, when one of them suddenly burnt out on a test. That alternator was designed for a nominal load of 8000 kw. and 12,000-kw. overload for two hours. It had been running at normal rating and then increased rapidly from 8000 kw. to a load of 12,000 kw. It had only been running at 12,000 kw. for less than an hour when it burned out with the thermometer on the end windings showing a total reading of only 85 degrees. That showed, of course, at once that there must have been some parts of that machine a good deal hotter than 85 degrees. It was suggested that possibly some scheme of exploring coils would be advisable. When that machine was rewound, exploring coils were put into that machine. It took only a very few months of experience to prove quite conclusively that the preceding practise of building and designing turbo-generators involved at least two fallacies: First that there was a very great difference between the temperature as recorded by the thermometer and by the exploring coil; second, that the windings reached a constant temperature when operated at 12,000 kw. in about fifty minutes.

That demonstrated the fallacy of rating generators of that kind on a two-hour overload. In other words, the experience indicated that such a machine gets about as hot as it will ever get at the end of an hour. This finally resulted in rating such turbo-generators on a maximum continuous basis without an overload in addition.

P. M. Lincoln: Mr. Lamme starts his paper by stating that it is rather surprising that we had not gathered more information concerning the laws of temperature distribution and heat dissipation.

This after all is not so surprising, when we come to consider the difficulty of dealing with heat measurements. We have no heat ammeter or heat voltmeter or heat wattmeter, and thus it is exceedingly difficult to get the data on the amount of heat flowing, and the differences in thermal voltage, if we may call it so, that is, differences in temperature which cause heat flow. It is the inherent difficulty in securing these measurements that is, to a large extent, responsible for our lack of information upon this subject; I can testify, from my own study, that there is a very decided lack of information upon this general question of heat flow.

In referring to the comments of Mr. Foster, I want to call attention to one point. He states that the more rapid the air flow across a surface from which heat is being dissipated, the more rapid will be the escape of heat.

Now, that is perfectly true up to a certain limit, but beyond that limit it ceases to be true. That is, the friction of the air upon the surface will give rise to heat of itself, and we cannot carry the speed of air across surfaces up indefinitely and expect the escape of heat to continue to be dependent upon this rate of air movement. In our modern turbo-generators, we are getting very close to that point. The rise of temperature through the generator, due to the windage within the generator, is a very considerable amount, and we cannot force it a great deal higher than we are now doing in our modern generators.

Now, coming back to this question of allowable temperatures in generators: I do not think that there is any one who has given critical thought to the subject who will deny that it is perfectly safe with our modern insulation to go at least to 150 deg. cent. The real question is, how much further can we go? The standards committee of the A. I. E. E., I understand, placed this limit of 150 degrees, because they felt that there was not a sufficient amount of practise in the past to justify their placing a higher limit. When we come to consider, however, the actual point of danger in our modern insulations, and the experiences we have had with them, I see no reason why we should not go higher than 150 deg. cent. Just how much higher, is the question. I have devoted a little time to studying that question, and I think we can say that there is a definite limit beyond which we cannot go in temperature, that definite limit depending to a very large extent upon the temperature coefficient of the thermal conductivity of the insulation employed.

Let me put it down in figures. Suppose we have a coil, like an armature coil in a generator, insulated, and we put a certain current through that coil; it will of course have a certain amount of watts produced in it which I will call W_1. If we call I the current in the coil, and R its resistance, this wattage is equal to $I^2 R$, a familiar expression. We can go further. The R is dependent upon the temperature of the coil. If we take R_0 as the resistance of the coil at 0 deg. cent., its resistance at any other temperature is given by the well known expression $R = R_0 (1 + at)$ where t is the temperature in degrees cent., and a is the temperature coefficient. Therefore, the watts entering the coil are $W_1 = I^2 R_0 (1 + at)$. The usual value assigned to a is 0.004.

The watts that escape from the coil, which I will call W_2, are evidently proportional to thermal drop and inversely proportional to the thermal resistance. If therefore, we call t the temperature of the copper of the coil, t_1 the temperature of the cooling medium (surrounding air) and e the thermal resistance, the watts escaping, W_2 become $W_2 = \dfrac{t - t_1}{e}$

Now, this quantity e also has a temperature coefficient; and if we represent this coefficient by a', the expression for W_2 becomes $W_2 = \dfrac{t - t_1}{e_0 (1 + a' t)}$ where e_0 is the thermal resistance at 0 deg. cent.

Now Mr. Lamme has enunciated the general principle in his paper, that heat conductivity and electrical conductivity have a certain relation to each other, that they are roughly proportional to each other.

Now, if we assume—and this is the big *if* in my calculations—if we assume that the above law holds with respect to the temperature coefficients both of thermal and electrical resistance, that is, that a' is equal to a and that a has its usual value of 0.004—it can easily be shown that when the temperature exceeds 250 deg. cent., above the cooling medium, it comes into a state of unstable equilibrium. In other words, the amount of heat generated, increases with increasing temperature while the ability of the coil to dissipate heat decreases with increasing temperature. Evidently, there must eventually come a point where the coil is unable to get rid of the heat put in and the temperature tends toward infinity. Furthermore, the I^2R that gives a temperature of 150 deg. cent., will only have to be increased about 25 per cent in order to arrive at 250 deg. cent.

Let me put this in graphic form. Refer to Fig. 1, where temperature in degrees cent. is laid off on the vertical axis and the watts on the horizontal axis. The straight line marked W_i shows the manner in which the watts input to our coil, will vary with changing temperature, and the curve marked W_s will indicate how the watts dissipated will vary under the same conditions. In plotting this curve, the cooling air is assumed at 40 deg. cent. It is of course, obvious that the watts put in and the watts taken out, must be the same; that is, $W_i = W_s$.

If these two curves are made to intersect at 150 deg. cent. (the maximum now allowed by the Rules of the A. I. E. E.) the curve W_i will have a given inclination. If we increase this inclination by about 25 per cent, we will arrive at the point of tangency between W_i and W_s, and it is obvious that for higher inclinations, W_i and W_s will never meet. The point of tangency between W_i and W_s therefore, fixes definitely, a temperature beyond which it is impossible to operate.

Now, if we go further and put a "b" term into our temperature coefficient equation and give it the form $R = R_0 \, (1 + a\,t + b\,t^2)$ the point of tangency is further reduced and with the usual values of a and b, the maximum allowable temperature becomes about 200 deg. cent. above the cooling air.

The crux of what I have to say, comes in the assumption that temperature coefficient for thermal conductivity is equal to that for electrical conductivity. Now, I am simply making that assumption, and above results are based on that assumption. Whether that assumption is correct or not, I do not know. I have not been able to get any accurate data on this point. But if they are equal, the above results follow.

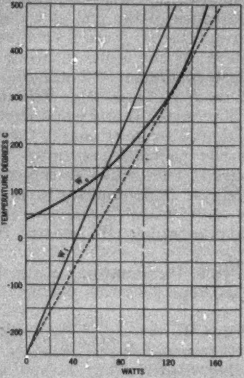

Fig. 1

Mr. Lamme has shown that some of the heat in a generator, escapes by flowing along the copper, and we do know that the temperature coefficient for thermal resistance of copper, is a quantity very close to that for the electrical resistance. However, most of the heat in our generator, escapes by flowing through the insulation and on the temperature coefficient of the thermal resistance of this insulation, there are practically no data available. Upon the value of this quantity, depends the amount of curvature of W_s in the Fig. 1 and the point of tangency obviously depends upon the degree of the curvature. I would strongly urge that steps be taken to obtain accurate data upon this point, covering the standard insulations that are used in electrical machinery.

W. C. Bauer: There is a very important point in temperature discussion which is very seldom brought up, and it is this: Some manufacturers seem to fail to realize the double function which insulating material must perform. It is used, of course, to limit the flow of current along the desired path and to keep it from short-circuiting along other paths. The manufacturer says, "The more insulation, the better my machine becomes." He fails to realize that the more insulation he puts on the more difficult it is for heat to get out; and there may be a point reached when, if he puts on four layers of insulation, the machine is not as safe as it would be if he put on only one layer. I do not know to what extent research along this line has been carried out, but what I think should be carefully investigated, is, the safety of the machine as a function, not of the thickness of the insulation but as a function of the thinness of the insulation.

N. J. Conrad: The authors emphasize the idea that the operating engineers usually measure temperatures at points which operate at relatively low temperatures as compared to the "hot spots", and also that measurements made with exploring coils or resistance coils are crude as compared to measurements made with thermocouples.

Ten years ago, and also later, we found it quite difficult in some cases to convince the designers that the temperatures indicated by exploring coils, were not considerably higher than the actual maximum temperatures existing in turbo-generators.

The Commonwealth Edison Company began the use of exploring coils the early part of 1907 by installing them in an 8000-kw. turbo-generator while it was being rewound after a burnout which occurred during an overload test. This generator had an overload rating of 12,000 kw. for two hours. It is interesting to note that in this case the exploring coils were placed between the two armature coils in the slots, which is now recognized as the best location.

Some of the facts brought out by this installation of exploring coils were very interesting.

With a load of 10,000 kw., the maximum temperature rise, obtained by means of an exploring coil between armature coils in the slots, was 78 deg. cent. while the average rise of four such coils was 73 deg. cent. The maximum rise, as indicated by four thermometers placed at the hottest spots that the thermometers could be placed, was 56 deg. cent., while the average rise of the four thermometers was 48 deg. cent. The difference between the maximum rise by exploring coil and thermometer was 22 deg. cent.

At the time that this generator burned out while carrying a load of 14,000 kw. the thermometers placed on the windings indicated a temperature rise of 58 deg. cent. The highest load tests run on this generator after it was rewound with the old type of winding and with exploring coils installed, were at 10,000 kw., but extended curves of temperature rises show that at 12,000 kw. the temperature rise would have been about 94 deg. cent.

A check test was made on these exploring coils in the following manner. The machine was run with a load of 9000 kw. until the temperatures indicated by the exploring coils were constant. The average temperature as shown by 10 exploring coils was 86 deg. cent. The load was taken off and the machine shut down. It required three minutes to take the load off the machine and 18 minutes more for the machine to come to rest after it was taken off the system. When the machine came to rest the average temperature, as indicated by the exploring coils, was 61.5 deg. cent., while the average temperature, as indicated by armature resistance measurements was 63 deg. cent. The decrease in temperature, between the time the load was decreased and the time the machine came to rest, was 25 deg. cent.

A matter which has not been mentioned in these papers is the importance of periodic heat tests in connection with increased heating caused by the accumulation of dirt in turbo-generators.

Temperature readings were taken on a 12,000-kw. generator with a load of 8,000 kw. The maximum rise of the copper with this load was 55 deg. cent. The maximum rise of the core was 62 deg. cent. These temperature rises were very much higher than usually obtained with this load on machines of this particular type. The normal temperature rise at 8000 kw. being 32 deg. cent. for the copper and 28 deg. cent. for the iron. It was hardly reasonable to suspect that the accumulation of dirt in the machine would cause such a large increase in the temperature rise. It was, however, decided to remove the field and make an inspection.

It was found that one of the bearings of this unit had been throwing oil. This, combined with the fact that a great deal of building reconstruction had been going on, had resulted in a very great accumulation of dirt on the armature. In fact this accumulation of dirt was so great that about 90 per cent of the ventilating ducts had been entirely choked up. The increase in temperature rise amounted to 80 per cent on the copper and 123 per cent on the core.

C. A. Keller: Referring to Mr. Lamme's statement that one great advantage of the thermocouple is its very small size, so that it indicates the temperature at practically a point instead of a very considerable area. This type of temperature coil may be desirable for factory tests, but after the machine has been in service for some time and the slots and openings partially filled with dirt collected from ventilating air, a temperature coil with considerable area to cover some of the hot spots which it is difficult to ordinarily predetermine would be more practical.

I wish to ask Mr. Lamme if there has been any scheme devised for taking temperatures in rotating elements such as the armature of a railway rotary while running under load conditions.

M. M. Flower: There is one point I do not think has as yet been brought out very clearly. Mr. Newbury has brought out clearly the limiting features of the rotor temperature. The limiting feature is the exciter voltage and not the temperature rise. The temperature rise in the rotor can never become dangerous, or in other words, the exciter voltage acts as a safety valve, which will always limit the temperature rise in the rotor. This limitation does not exist on the stator as the operator can keep on loading the generator until the safe temperature limit of the stator is exceeded.

B. G. Lamme: I have made up a sketch which brings out much better than any description, some of the fundamental differences between Class "A" and Class "B" insulations. These might be called the time-temperature curves for these insulations. These must be considered as approximations only, as, from the very nature of the materials themselves, no exact curves are possible. The important feature to be considered in the curves, is the general shape rather than any absolute values.

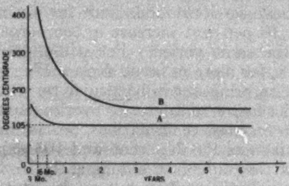

FIG. 2

We have made a great many temperature tests of insulations to determine their durability; also we have made examinations of a very large number of windings which have been in service for many years, but for which we had only approximate data as to temperatures. Obviously it is impracticable to carry on an accurate life test covering a long period of years, so what we did in most of our tests, was to carry the temperatures up to such points that destruction was either reached or indicated in a comparatively limited period of time.

In Fig. 2 curve *A* indicates approximately the durability of class A insulations for various temperatures. This should be recognized as being approximate, but it is optimistic rather than pessimistic.

Curve *B* applies to well built class B insulations, as now furnished by some of the electrical manufacturing companies. Such insulations contain a large percentage of heat resisting materials with a comparatively small per cent of binding material and the insulation is applied so tightly that deterioration or destruction of the binder does not appreciably loosen up the true insulating material.

Considering curve *A*, taking 105 deg. cent., as the ultimate temperature limit for long life without undue deterioration, then with a very slight increase in temperature, say to 115 deg. cent., the life is shortened very much, and at 125 deg. cent. such insulation is good for only a very few months at the most. At 150 deg. cent. it has an exceedingly short life.

Next considering curve *B*, our available data indicate that for over twelve months operation at 200 deg. cent., the insulation is in first class shape; in fact, much better than class A insulation at 110 deg. cent., for the same length of time. At 300 deg. cent. for six months, the insulation really shows better than class A insulation at 115 deg. cent. for the same length of time, and, at 400 deg. cent., the class B insulation for three months is better than class A insulation at 125 deg. cent. for the same length of time. If we now assume the continuous life for the class B insulation as 150 deg. cent., then it is seen that a 33 per cent increase in temperature for one year is no more harmful than a 5 per cent increase in temperature over the 105 deg. cent. for class A insulations for one year. Also a 100 per cent increase in temperature above its continuous limit for six months is comparable with a 10 per cent increase in temperature for class A insulation for the same period. For still higher temperatures the percentage is far more in favor of class B.

What I want to bring out in particular by means of this diagram, is that the factor of safety for overloads is vastly greater for class B than for class A insulations, on the basis of continuous life being taken as 150 deg. cent. and 105 deg. cent., respectively. Part of this difference is inherently in the characteristics of the materials themselves, but no doubt part of it is due to the fact that the arbitrary 150 deg. cent. limit set for properly built class B materials is considerably too low in comparison with 105 deg. cent. for class A. But, whatever the explanation, the difference is there.

In regard to the very high temperatures for class B insulations, such as 300 deg. and 400 deg. cent. shown in curve B, attention should be called to the fact that unless there is an exceedingly high temperature drop through the insulation itself, any outside supporting layer or wrapper of fibrous materials is liable to become unduly heated and may disintegrate. Therefore, while the insulation proper might stand 400 deg. cent., for instance, yet if this was continued for any considerable length of time, so that the outside supporting material became excessively heated, such material would have to be of something else than the usual treated tape or fibrous wrappers. However, it so happens that very high temperatures are rarely attained in practise, except in the case of armature conductors buried in slots. In such case the surrounding iron assists very materially in cooling the finishing wrapper on the coils, unless the high temperature is maintained for a very considerable period.

Some are inclined to look askance at mica at 150 deg. to 200 deg. cent., but it must be remembered that in certain heating apparatus mica is used up to 500 deg. cent. and, in some cases, even up to 750 deg. cent. Practically all micas will stand up to about 600 deg. cent., without undue deterioration, and some grades will stand up to 1000 deg. cent. From this viewpoint, the temperature of 150 deg. to 200 deg. cent. in armature coils appears to be very low and the whole matter turns upon the way such mica is used. If the percentage of mica in the insulation is relatively high and the mica is put on so tightly that the binding material can disintegrate and loosen up and yet the natural elasticity or springiness of the mica can hold the insulation tightly in place, then such insulation can stand very high temperature without injury. But, if the mica is wound or placed so loosely that this disintegration of the binding or supporting material allows the mica part to loosen up materially, then the insulation qualities may still be very good from the dielectric standpoint, but may be in such poor shape mechanically that vibration or shocks may shift it or displace it sufficiently to injure it as an insulator. The defect here is a mechanical one and not in the quality of the material itself.

Mr. Junkersfeld has spoken of some of his early experiences with high temperature, and he mentioned that the data which he and his associates obtained have had a marked influence in leading the manufacturers toward better grades of insulation. This is no doubt correct, but I wish to call attention to the fact that the manufacturers were also following this matter independently of the operating companies, with the same end in view. For instance, the company with which I am associated, insulated the 1894 Niagara generators with mica. We did not know whether such insulation was required, but we thought it was good material and so put it on. Later tests showed that this was a very fortunate decision, and now, after twenty years of operation, this insulation is still in very good shape, although subjected to very much higher temperatures than originally contemplated, 150 deg. to 200 deg. cent. being not uncommon according to later tests.* Also in 1898 and 1899 the large engine-type Manhattan Railway generators had mica insulation, in the form of wrappers, on the armature coils. Following this, mica insulation was used for quite a number of years, mostly on large high-voltage alternators. About 1904 we built some large capacity 60-cycle turbo-generators on which we used mica wrappers on the armature coils. In service, one of these machines was injured from some mechanical cause and we had to rewind it. One of the fads about this time was special oiled-linen tape insulation, and quite a pressure was brought to bear upon us to rewind this machine with such oiled tape. With this insulation the armature broke down in a comparatively short time (within a few months, if I remember rightly). When the coils were removed, the outside layer of insulation next to the iron was found to be apparently in fair shape, but next to the copper the insulation showed indications of being excessively heated; in fact, it was badly carbonized in some places. We then reinsulated with mica and the machine was operated for many years without trouble. Here was a direct comparison between class A and class B insulations. I do not know how hot those coils ran, but, judging from the appearance of the oiled-tape insulation, it must have been materially above 125 deg. cent. Here was a fortunate instance where the machine was first insulated with mica tape and then afterwards insulated with fibrous materials, so that actual comparison was obtained with the two materials. This was ten to twelve years ago, so that it cannot be said that experience showing the relative merits of these two types of insulation is only of recent date.

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*TRANS. A. I. E. E. 1915, Vol. XXXIV., Part 11, p. 2747.

In the same way similar experience was obtained with field insulation. Practically all our early turbo-generator fields were insulated with fibrous sheet materials. Numerous instances occurred where such insulations deteriorated so much that rewinding was required. This led to numerous tests for temperature. In some of these earlier machines there was evidence of practically uniform overheating throughout the whole winding, thus indicating practically uniform temperature. In such cases it was comparatively easy to approximate the ultimate temperature from readings of the field currents and the field volts, thus obtaining the increase in resistance and from this the temperature rise. Such tests soon developed the fact that temperatures of 110 deg. to 125 deg. cent. were not uncommon on the earlier turbo-fields, while with the increased capacities and higher speeds, toward which we were continually tending, the indications were that still higher temperatures would be attained. This led to the development of mica insulation for the field windings of turbo-generators. In 1906 and 1907 a number of the earlier hot fields were rewound with mica and such fields have been operating up to the present time, or until discarded in favor of larger units. The record with these mica insulated fields has been extremely good. In some of the tests which we made on these earlier machines to determine the suitability of mica for field insulation, we carried one field up to 250 deg. cent. for forty-eight hours, and would have continued the test very much longer, but the conduction of heat from the core through the shaft to the bearings was sufficient to overheat them. However, at the end of this test the insulation was found to be in absolutely good condition. This was a very mild test, in view of our later investigations on mica, but at that time it was considered wonderful. I am simply bringing up such points to indicate that mica has been used quite extensively on turbo-generators for many years.

I was much pleased to hear Mr. Conrad's remarks regarding the effects of dust and dirt in limiting the ventilation of high-speed machines, and in turbo-generators in particular. Very few people have any conception, in the case of turbo-generators, as to how much air is put through the machines. A modern turbo-generator puts through itself practically its own weight of air every forty to sixty minutes. If there is a very small per cent of dust in this air and it lodges in the machine, it is obvious that it will not take long to clog up the ventilating passages. However, dry dust appears to go through the machine with very little deposit. Apparently the velocity of the air is sufficient to keep the dust moving. But, if there is a little free moisture in the air, or a little oil in any form, then such moisture or oil lodging on the surfaces of the ventilating passages will collect dust and eventually interfere with the ventilation. Such interference appears in two ways—it covers the heat dissipating surfaces with a poor heat conducting material, and it also cuts down the cross section of the air path and thus reduces the amount of air which can get through. In one case of a turbo-generator which I examined, the inlet passage at the air gap appeared to be much smaller than when the machine left the factory. There appeared to be a ridge of iron projecting inside the iron laminations. I tried to cut it with a knife and found it almost as hard as iron, but it developed that it was a mixture of dirt and oil which had solidified at this point. We had a second case of this sort where a turbo-rotor burned out after about a year's operation. Upon dismantling the winding it was discovered that the roasting was all at one end and that the other end was in good condition. Further investigations showed that the ventilating passages at the one end of the machine were almost completely clogged up, while at the other end they were fairly open. It was then found that a small amount of oil had leaked into the machine in the form of fine spray and this had caused the trouble.

In modern machines this problem of dirt is taken care of in many cases by air washers. The functions of the washer is principally to remove dirt, but it does cool the air a little, but this is of minor importance compared with the other effect.

Mr. Keller asked whether there is any effective method of measuring temperature in rotating apparatus without shutting down. In case of rotating fields, a pretty good idea can be obtained from measurements of the field current and voltage during operation, these giving the increase in field resistance. This is a very good method in those cases where the temperature is reasonably uniform throughout the field winding. In turbo-generators it is apparently a fair approximation. However, in d-c. armatures there is no very effective method of determining temperature except by the thermometer. Thermocouples cannot very well be used on rotating apparatus due to the necessity for moving contacts to make connection with the external indicating apparatus. After a long series of investigations we found the results so variable that we gave up the method. Such tests, if successfully carried out, would require laboratory refinements which are not usually possible in ordinary commerical work.

F. D. Newbury: Professor Gray brought out a number of interesting points. I am glad to know that he agrees that the maximum safe rise is the proper guarantee, even though he questions whether engineers in general will accept it.

He stated that he doubted whether the purchaser would buy a high-temperature generator if there was the alternative of purchasing a low-temperature machine at the same price. That, however, is not the question. The question we are discussing is much broader than that. It is not the individual case that interests us, but whether in the long run the high-temperature machine is the more economical machine, the machine that should survive. If my opinion is correct, the high-temperature generator is the more economical generator and will be the generator of the future.

Professor Gray also stated that he did not think the exciter voltage should be a limit to rating. Such an easy thing to overcome should not be permitted to become a limit. That, however, is begging the question. While it is an easy matter to provide any desired margin in exciter voltage (although at the expense of increased exciting current), it is not possible to provide the heat dissipating capacity in the rotor that would be necessary in order to use the higher exciting voltage. In many stations there is a common exciter bus maintained at a definite voltage. In such cases, the exciter voltage, directly, is a limit to rating.

Professor Gray also spoke of the higher voltage of armature windings as compared with windings on rotors. Practically all the larger machines, even the 13,000-volt machines, have only one or two turns in each armature coil, so that the problem of insulating between turns is not a difficult one.

Mr. Foster brought up a number of interesting points in connection with generator design, to some of which I must take exception.

Mr. Foster stated that the use of Class B insulation was not justified in all cases. It is justified in my opinion in all the cases that we are now considering; that is, in large, important machines.

For the reasons brought out in Mr. Lamme's discussion, there is no margin of safety if fibrous insulation is used in machines with a temperature rise of only 60 deg. measured by thermocouple. Even though the temperature rise is 60 deg., it is not wise to use fibrous insulation in important machines where reliability is so important. The difference in margin with fibrous insulation and with mica insulation is very well brought out by the tests Mr. Lamme mentioned. We found it very easy to cause the cotton, linen, or paper insulations to fail after a few weeks' test at 150 deg. In no case were we able to break down properly constructed mica insulation with temperatures up to 400 deg. In my mind there is no question that with Class B insulation subjected to 150 deg., the margin of safety is very much greater than with Class A insulation at 105 deg.

But this question of safety at 150 deg. has been discussed before the Institute at a previous meeting and it was quite generally agreed that 150 degrees was safe. Mr. Foster concurred in this opinion.*

Mr. Foster correctly stated that mechanical stresses limited the amount of copper that could be carried by the rotor, but that no such limitation existed in the case of the stator. Consequently, according to Mr. Foster's discussion, a very easy remedy for high temperatures in the stator was the use of deeper slots. He also very properly called attention to the dangers of excessive eddy-current losses in the armature winding of these large turbogenerators. But to deepen the slots is incurring the danger of eddy currents, and it is very easy to increase the loss by the addition of copper instead of decreasing the loss. So there is, in my opinion, no remedy for high armature-coil temperatures that does not involve an appreciably larger generator.

Professor Bauer brought up the interesting point that increasing the thickness of insulation, while it increases the safety of the machine by an increase in dielectric strength, decreased its safety by increasing the temperatures. It illustrates the point that the design of machines of this class is a series of compromises. Safety in mechanical stresses must be balanced against safety in temperature; safety in insulation against safety in temperature, and so on through the list. Any advantage we can gain through the use of better materials is an advantage in the direction of a more economical and better machine.

Mr. Keller mentioned the advantage of a long resistance coil as a means of measuring temperature, as opposed to the short thermocouple. I might explain that the thermocouple is merely a welded junction of two metals, and as constructed is a quarter of an inch wide, (6.35 mm.) and the junction is practically a line; so that it does, as nearly as any device we know, measure the temperature at a particular point. The resistance coil, on the other hand, has to be fairly long in order to obtain a sufficiently high resistance in the coil to make it accurate; and if it is to measure temperatures above 100 deg., the adjacent turns must be separated, so that with the deterioration of the enamel or silk insulation on the wire, the turns will not short-circuit. Resistance coils may be anything from six inches (15.24 cm.) up to a couple of feet in length, so that the resistance coil indicates the average temperature through that length. The thermocouples can be ruggedly insulated with mica so that they will withstand any temperatures that the coil insulations will withstand. For these reasons, I prefer the use of the thermocouple, but, after all, the main thing is that one or the other be used, and internal temperatures be determined.

Mr. Fowler made the point that a higher temperature was allowable in the rotor than in the stator, because the available exciting voltage placed a limit upon the current that could be circulated in the rotor, while no such limit existed in the case of the armature. The armature current, however, cannot be increased beyond the corresponding maximum available field current unless the armature voltage is allowed to fall. So that the same safety stop exists in the case of the armature as in the field, unless the generator voltage is allowed to decrease in case of overloads.

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*Trans. A. I. E. E. 1915, Vol. XXXIV, Part II, p. 2767.

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RUPTURING CAPACITIES OF OIL CIRCUIT BREAKERS

BY STEPHEN Q. HAYES

Abstract of Paper

This paper is really a series of more or less disconnected notes dealing with the question of rupturing capacity of oil breakers. It makes no attempt to go into the theory of circuit-breaker design, and its main object is to open up a discussion regarding the advisability of using the term "Maximum Safe Rupturing Capacity" to describe the result obtained by the root-mean-square of the maximum peak of the current wave that occurs while the breaker is opening, multiplied by the root-mean-square of the open-circuit voltage that occurs immediately after the breaker opens. Attention is called to the different ratings due to use of peak values and root-mean-square values of current and voltage.

It is recommended that an oil switch or an oil circuit breaker should be given a rating on the basis of maximum safe rupturing capacity that it can handle, and that a breaker after opening a short circuit up to its rating, should be immediately reclosable, and able to again open up a similar short circuit; breaker should open three successive short circuits before contacts need be repaired or oil replaced; these short circuits may be as close as two minutes apart.

THE OBJECT of this paper is to suggest the proper basis for the guarantees to be made by manufacturers of oil circuit breakers or switches to enable the prospective user to determine the suitability of the breaker to the proposed service conditions. This guarantee should be a specific statement of what the oil switch can do, and should preferably be free from any assumptions as to reactance in circuit, generator characteristics, use of relays or similar features.

It is self evident that oil circuit breakers for large power systems must be suitable for the service they are to perform, their current-carrying parts must be ample, their insulation good, and they must be capable of rupturing any amount of current they may be called upon to open. Such breakers should not only clear the circuit, but should be immediately reoperative without the necessity of inspection, adjustment, or repair, although inspection is advisable at the first suitable opportunity.

The term "ultimate rupturing capacity," as usually employed by American switchgear manufacturers has been applied in such a manner that it really meant the maximum size of system on which a breaker could be safely used, and even when used in this manner, it was necessary to explain fully, the basis of calculation, and the various assumptions that had been made. This method of rating, involves the momentary and sustained short-circuit characteristics of the machines, the various reactances in the circuits, the speed of tripping of the breakers, and other similar features.

It has been standard practise to assume that the breaker is connected directly to the buses, and may have to open any amount of current that can be received from that bus in case a short circuit of negligible impedance occurs just beyond the breaker. In most cases it is the reactance of the circuit rather than the resistance, that limits the current flow at times of short circuit, so it is usual to consider the reactance rather than the impedance of the circuit in calculating current flows. For cable systems or high-tension transmission circuits, the capacitance has to be considered. All of the generators and other synchronous apparatus connected to the bus, will tend to feed into the short circuit whatever current they can deliver under these conditions, this current as a rule, being limited only by the inherent reactance of the machines, and any external reactance that may exist between the machines and the point where the short circuit occurs.

Due to inertia, it is impossible to have a breaker trip out instantaneously, consequently no breaker is ever called on to open the momentary short-circuit current that occurs during the first few cycles, but it has to be strong enough mechanically to resist the magnetic stresses set up during such a short circuit. With a-c. coils energizing the mechanism direct from the current transformers, large capacity breakers can be made to open in about 0.2 second. With the usual shunt trip relays, the time of opening is about 0.3 to 0.5 second, while with time-limit relays, the opening can be delayed either for some definite time, or for a time that varies inversely with the load. With a non-automatic breaker, the time of opening is left to the discretion of the operator. As most generators reach the condition of continuous short-circuit current in not over 0.8 second, it is figured that a definite time limit of two seconds or even less, secured through a relay, is equivalent to non-automatic service, in so far as rupturing requirements are concerned.

Whether a breaker is to be used for automatic or non-automatic service, it can only open a certain fairly definite amount of power at the arc. This amount being fixed, it should be noted that for non-automatic service, the size of plant to deliver this would be determined by the sustained short-circuit characteristics of the generators, and other synchronous apparatus. For automatic service, this same amount of power could usually be delivered by a smaller plant, as the momentary short-circuit current is almost always higher than the sustained.

In order to allow for certain of these variables due to the machine characteristics, one American manufacturer gives ratings for his oil switches for automatic and non-automatic service for two classes, A and B, the latter being systems where one or more generators are of the turbo type with reactances of less than 8 per cent and the former applying for all other systems.

This A and B method of rating based on data published some years ago assigned for most of the smaller sizes of breakers about 25 per cent greater rating for the non-automatic A class than the corresponding non-automatic B, the automatic rating for the A class was usually about 50 per cent of the non-automatic A and the automatic B rating about 33 per cent of the non-automatic. On the larger sizes, however for 15,000-volt service, one size was rated 70,000-kv-a. class A non-automatic, 56,000-kv-a. class B non-automatic, 70,000-kv-a. class A automatic and 46,000-kv-a. class B automatic.

It would seem that the automatic service would be more severe than the non-automatic and the breaker may be under rated for non-automatic or over rated or automatic.

The class B service is based on using turbo generators of 8 per cent reactance or less. Usually such machines have a lower sustained short-circuit rating than water-wheel-driven units of higher reactance than 8 per cent, so that there would be less current for a non-automatic breaker to open in a 20,000-kv-a. plant fed from turbo generators, than a similar plant fed from water-wheel generators. On this basis the non-automatic B rating should be higher, not lower than non-automatic class A.

Another American manufacturer explains the ratings assigned by using a standard assumption of generators or other synchronous apparatus, having an average reactance of 8 per cent, a momentary short-circuit current of 12½ times normal falling to half of this amount, or 6¼ times normal by the time the breaker opens, and a continued short circuit of one quarter, or three times normal. With this explanation, it is evident that a breaker rated as having 10,000-kv-a. rupturing capacity should be capable of handling 62,500 kv-a. at the short circuit. This same breaker for non-automatic service where the machines are assumed as delivering three times normal, could, therefore, be used on a 20,000-kv-a. system, or would have a non-automatic rating of 20,000 kv-a.

This relative method of rating automatic and non-automatic breakers only holds true for the one set of assumptions made, and will be incorrect when applied to a system fed from low-reactance machines having a high momentary short-circuit value and a low sustained short-circuit value. The statement that the automatic rating could be multiplied by 6¼ to determine the amount of power the breaker could rupture gave some real data regarding the rupturing capacity.

In comparing the nominal rupturing capacities, the one line of breakers was usually given its class A automatic rating while the rating of the other line was the instantaneous overload rating practically corresponding to the class B automatic.

In systems of large generating capacity, where current limiting reactors are used, or where the reactance of transformers and lines may limit the current flow on short circuit to a point well within the capacity of the system to supply continuously, it will be found that the breakers provided with time-limit relays, or used for non-automatic service, have as severe rupturing conditions to meet as those used for automatic service.

These methods of rating are not directly applicable in all cases, and are open to many objections, and do not readily take into account certain features that really are vital in determining the adaptability of breakers to specific service. The rate at which the short-circuit current of a generator dies down varies with its design, so that the short-circuit current of a generator may die down from the initial rush to the continuous short-circuit value in a period of time ranging from 0.2 to 0.8 second. The initial wave may be as high as 20 times normal, and the continuous short-circuit value may be as low as 1.4 times normal.

In case of an unsymmetrical wave, experience seems to show that the strain of opening does not differ appreciably from that produced by a symmetrical one. A current wave ranging from a positive maximum of 10,000 amperes to a negative one of 2000 amperes can be taken care of as readily as one ranging from plus 6000 to minus 6000. This may be due to the longer time required for the arc to reestablish itself in the case of the unsymmetrical wave where the negative maximum is small. By the time the breaker actually opens the circuit, the amount of assymmetry has greatly diminished from that experienced during the first few cycles.

As most power circuits are three phase, the rupturing capacities assigned to circuit breakers are those applying to three-pole breakers on that service. The corresponding rating for two-pole breakers on a single-phase circuit is 70 to 75 per cent and the rating of a four-pole breaker on a two-phase circuit is considered 140 to 150 per cent of the corresponding three-phase rating.

Under some certain conditions, smaller switches could be used, for instance, in substations where limited transformer capacity is installed between the oil circuit breaker, and the line, or on substation feeders where a breaker of higher capacity is interposed between the breaker in question, and the substation bus.

When considering switches for connection to buses fed from the generator units of motor-generator sets, the capacity of the system supplying energy to the motor-generator set, need not be considered. In such cases, the sum of the rated capacity of the generator units, on the motor generator sets should come within the limits assigned to the breakers.

The kv-a. ratings usually assigned to breakers are based on the listed voltage rating of such breakers, and any change in operating voltage from the listed voltage rating will usually change the kv-a. rating in about the same percentage, that is, an increase or decrease in voltage of 20 per cent would decrease or increase the kv-a. rating by the same amount.

While this percentage rule is not strictly adhered to, a typical example might be noted of a certain moderate capacity breaker designed for 22,000-volt service with a nominal rupturing capacity, assigned by its builders, of 10,000 kv-a. at 22,000 volts, 12,000 kv-a. at 16,500, 13,000 at 13,200, 17,000 at 7500 and 19,000 at 4500 volts or less.

On the assumption, more or less justified, that the strength of the breaker tops, insulators and fittings have been properly proportioned to the tank strength and that the speed of opening is satisfactory the rupturing capacity of an oil breaker may be considered as a function of the tank dimensions.

When a breaker has been installed, it should be remembered that with increase in capacity of system, failure to maintain breakers either as regards mechanism or insulation, changes in reactance, changes in method of operation and defective relays may so change the duty on a breaker as to lead to its destruction.

Almost all of the oil switches and oil circuit breakers now in service, are operating satisfactorily, but it is realized that they are far from perfect, and it is possible that some of the commercial breakers being sold, are over rated. By having some definite rating in kv-a. to work to, breakers of the smaller sizes could be tested to see that they actually met their guarantee.

In order to simplify this question of breaker rating, it is proposed to use "maximum safe rupturing capacity," or some similar term to describe the result obtained by the root-mean-square of the maximum peak of the current wave that occurs while the breaker is opening, multiplied by the root-mean-square of the open-circuit voltage that occurs immediately after the breaker opens.

All modern transmission systems employ generating apparatus giving essentially a sine wave for current and voltage, which sine wave has a ratio of peak value to root-mean-square value of 1.4 to 1. A breaker capable of rupturing 10,000 amperes maximum value at 10,000 volts maximum value, if rated on the root-mean-square basis, would be considered capable of handling 7100 amperes at 7100 volts, or would be given a rating of 50,000 kv-a. If the peak value of the current, or 10,000 amperes, is used with the root-mean-square value of the voltage, or 7100 volts, the rating would be 71,000 kv-a. If the peak value of the current, or 10,000 amperes, is used with the peak value of the voltage, or 10,000 volts, the rating would be 100,000 kv-a. All of these ratings would cover the same duty to be performed, but as all power measurements are regularly based on the root-mean-square values of current and voltage, this is undoubtedly the logical basis for circuit-breaker rating.

The kv-a. rating obtained as above is that which this breaker should be guaranteed to open, the breaker being immediately reoperative, without the necessity of replacement of oil or adjustment of contacts. It might be well to fix this rating at such a point that the breaker could be guaranteed to open this amount at least twice, and to be immediately reclosable, and in condition to open the same circuit kv-a. the third time.

In a-c. railway work, and similar installations where repeated short circuits are apt to occur, the breaker should be capable of opening such a short circuit at least ten times within the course of an hour; such short circuits not occuring closer together than two minutes to allow time for the gases that may be formed due to the short circuit to be properly vented from the breaker before a second short circuit occurs.

It might be pointed out that there is a difference between rating a circuit breaker in terms of the maximum kv-a. which it can open, and in terms of the maximum current which it can open. On certain systems with the machines of certain characteristics, heavy short-circuit currents are usually accompanied by reduced voltages and this point has to be given careful consideration. After opening a very heavy short circuit, thus relieving the system, the voltage frequently has a tendency to rise immediately to a point somewhat greater than normal, and this point should also be considered in the rating of the breaker; in other words, while a certain breaker might be able to open 10,000 amperes successfully where the circuit voltage immediately after the short circuit only went back to normal, it might not be able to function satisfactorily if the open-circuit voltage went up to points considerably above normal.

It is realized that it will be extremely difficult for an engineer to determine in advance exactly how heavy a short circuit it is possible to get at a given point on a transmission system, but from the view point of the manufacturer, it is simpler and better for him to make a definite guarantee as to just what service his breaker can accomplish, allowing the operating or designing engineer to determine whether such a breaker will meet the actual short-circuit conditions that may occur on any point of his system.

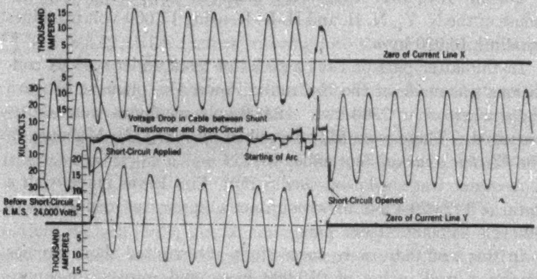

FIG. 1—60-CYCLE, THREE-PHASE SHORT CIRCUIT—142,620 KV-A. SYNCHRONOUS CONNECTED LOAD

It is a well known fact that formerly the opportunities of testing the actual rupturing capacities of the largest capacity oil switches and breakers were almost nil and that the capacities assigned were really intelligent estimates based on the testing to destruction of small units and calculation as to the increase in rupturing capacity secured by greater volume of oil, greater head of oil, increase in strength of tanks, extra volume of expansion chamber and similar features, while this is still true in certain cases a large amount of valuable data have been collected in the last few years.

Among the more important tests on the rupturing capacity of oil circuit breakers may be mentioned those described in the papers presented in June 1911 before the Annual Convention of the A. I. E. E. in Chicago, by Messrs. Schweitzer and Schuchardt and Mr. E. B. Merriam. These were made on a 12,000-kv-a., 9000-volt, 25-cycle turbo generator of the Commonwealth Edison Co.

In February 1910 tests were made at the Long Island City power house of the Pennsylvania R. R. with two 5500-kv-a., 11,000-volt, 25-cycle turbo generators.

During 1910-1911 tests were made at the Cos Cob power house of the N. Y., N. H. and H. R. R. using 11,000-volt machines totalling 16,000 kv-a.

In the latter part of 1911 a series of tests under various conditions was made at the Hydraulic Power Co. plant at Niagara Falls where four 7500-kw., 12,000-volt machines were short-circuited. These were fully described by Mr. J. N. Mahoney in the *Electric Journal* September 1912.

A recent test shown on oscillogram, Fig. 1 was made with a total of 142,620 kv-a. in synchronous apparatus connected to 60-cycle 24,500-volt bus bars.

In this test there were successfully interrupted short circuits having a peak value of 950,000 kv-a. and root-mean-square value of 475,000 kv-a. at the time the contacts opened, both symmetrical values at 24,500 volts, representing the largest amount of power ever used on such a test. The unsymmetrical value of the initial wave of the short circuit was 50 per cent greater representing 1,425,000 kv-a. As shown by the oscillogram the short circuit continued for six cycles on a 60-cycle circuit before the circuit-breaker contacts parted and continued for three cycles through the arc. This breaker used the same oil and same arcing tips for all the tests. The only external effect was a small amount of oil forced out through a defective joint between the tanks and frame.

Other tests at various voltages have been made as the basis of circuit-breaker ratings, and although these have not been published the manufacturers guarantees are usually based on real data and can be accepted by operators as being fairly conservative.

Presented at the 327th meeting of the American Institute of Electrical Engineers, Boston Mass., December 8, 1916.

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RATING OF OIL CIRCUIT BREAKERS

BY E. M. HEWLETT

Abstract of Paper

Paper points out several difficulties, which are encountered in the rating of actual circuit breakers, but generally favors that these ratings be on the basis of the current to be opened in the arc at the operating voltage of the system.

THE VARIABLE factors entering into the problem of rating oil circuit breakers make its solution very difficult.

Up to certain capacities it has been possible to determine definitely what oil circuit breakers will open. The experience of many years, during which oil circuit breakers grew from a few thousand volts for a few kilowatts station capacity, to 10,000 volts, 40,000 volts and higher voltages, for many thousand kilowatts station capacity, coupled with the facility of testing various designs under actual emergency conditions, has crystalized the requirements of circuit breakers of this kind and the constructive features of commercial design.

However, the capacity of stations is always growing, the forces dealt with are ever increasing, and consequently, new types of circuit breakers must be constantly developed, ratings of which cannot be based on actual past service. To test such circuit breakers systematically would be beyond the scope of any testing units at the disposal of any manufacturing company and would require the use of power stations of enormously high capacity.

The possibility of utilizing such power stations for the testing of circuit breakers is very limited, as in order to carry their connected load the big operating companies must generally have constant and instantaneous control of all their apparatus.

Thus, new designs of high-duty circuit breakers must, for the present, be rated mainly upon judgment based on past broad experience. For the engineer, the ideal way of rating circuit breakers is on the basis of the current which is actually opened in the arc at the operating voltage of the system, as in the present A. I. E. E. ruling. (This current in the arc is not the peak value of the short-circuit current curve, but is that value which prevails at the moment when the circuit breaker opens, at the point where it is installed.) However, in a rational design of circuit breaker, other factors must be considered besides current to be ruptured, primarily the power factor at the time of the event and the voltage regulation of the system. In the smaller capacities, these factors could be disregarded, as with them it has always been possible to allow very liberal safety factors without sacrificing reasonable proportions. We are therefore rating at the present time oil circuit breakers by arc current and system voltage up to certain capacities. As the capacities of the system and circuit breakers increase, as spacings and clearances become important design factors, and as materials employed in the construction of the circuit breakers must be used more nearly to their limits, it becomes necessary to take all conditions into account.

Oil circuit breakers for small stations and industrial service are often used by men who should not be called upon to figure the current and voltage values, which is necessary for selecting the proper type circuit breaker for their service.

For these conditions the kilowatt rating is most convenient, *i.e.* the total generating capacity of the system, or its equivalent, at the point of disturbance. Generally the kilowatt rating is based on the assumption, that the disturbance takes place so close to the generating apparatus, that reactance and resistance of connections between generating apparatus and the place of disturbance need not be considered. A certain initial reactance of the generating apparatus and a certain diminution factor of the current started by the disturbance, dependent on the time required by the circuit breaker to open the circuit after the disturbance has started, are assumed.

If the oil circuit breaker is located at some other point in the system with considerable line or transformer impedance between the generating apparatus and circuit breaker, allowance must be made for the current-limiting effect of this additional impedance. Instead of the generated kilowatt capacity, an equivalent kilowatt capacity must be used, which refers to the actual location of the circuit breaker in the system and is lower than generated kilowatt capacity, by an amount dependent on the characteristics of the intervening conductors and circuits.

The physical dimensions of the conducting copper parts of the circuit breaker should always carefully be considered. Conducting parts must be of sufficient size to carry the rated current indefinitely without objectionable temperature rise, also be large and strong enough for the maximum current rushes between the instant of short circuit and the time of opening of the circuit.

The use of current-limiting reactors, or reactances in transformers and machines in connection with systems is increasing. The reactor may be in circuit permanently or only when the breaker is opening. Various means have been developed to insert reactors or resistance into the circuit as the circuit breaker opens. While such arrangements reduce the current which the circuit breaker opens, they cannot act quickly enough to reduce the instantaneous maximum current and the shock on the system which is the real point to be considered.

Finally, one man will require the circuit breaker to open the most severe short circuits without the slightest indication of distress. Another man may be well pleased if the circuit breaker protects his more costly machinery, even if the circuit breaker itself is destroyed in doing so. Some one else may expect the circuit breaker to open two or possibly three times without requiring inspection or repair.

It is thus evident that there is a wide range of opinion as to what constitutes satisfactory operation; but as experience and information accumulates, this situation will gradually improve and we will approach closer to, and it is hoped will ultimately reach, the solution of the problem.

To sum up—I am in favor of rating circuit breakers on the basis of current in the arc and operating voltage of the system. The term "current in the arc" implies, that in defining its value all factors have been considered, which are necessary to determine the actual work to be performed at the time when, and at the place where, the current is interrupted.

I am not in favor of giving ratings to circuit breakers, in transient peak values which do not exist at the time of opening the circuit

DISCUSSION ON "RUPTURING CAPACITIES OF OIL CIRCUIT BREAKERS" (HAYES), AND "RATING OF OIL CIRCUIT BREAKERS" (HEWLETT), BOSTON, MASS., DECEMBER 8, 1916.

Chester Lichtenberg: The standardization of the rating of the interrupting capacity of an oil circuit breaker is fast becoming an economic necessity. Manufacturing companies have a wide variety of product to offer but operating companies have difficulty in choosing suitable devices therefrom, because the duty which they will perform is not published in standard form. Consequently, the rating suggestions made by Messrs. Hayes and Hewlett are timely and should encourage engineers to submit their ideas on this important topic in order that their knowledge may be utilized in arriving at suitable standards.

It seems desirable to rate circuit breakers on the basis of the current in the circuit during the time the arc persists in the breaker. There is, however, some question regarding the value of this current. It is described by Mr. Hayes as "the maximum peak of the current wave that occurs while the breaker is opening." It is defined by Mr. Hewlett as "that value which prevails at the moment when the circuit breaker opens." Neither of these seems quite clear nor comprehensive and in place thereof, it is suggested that, "the average of the r.m.s. values of the current peaks on the transient side of the true zero line as measured by an oscillograph, during the time that the arc persists," be taken as the current interrupted by the breaker, when interpreting test results.

Another question in considering the interrupting capacity of an oil circuit breaker is the pressure voltage of the circuit. Mr. Hayes proposes to use "the r.m.s. of the open-circuit voltage that occurs immediately after the breaker opens." This suggestion has much to commend it but unfortunately if it is adopted it may further complicate the rating, on account of the pressure variations which systems may exhibit. Mr. Hayes has mentioned some of these. Besides, during ordinary switching conditions, the circuit pressure may rise momentarily to about three times normal, and under unusual conditions, it may rise as high as seven times normal just after the breaker clears the circuit. It is quite important, therefore, that if the breaker rating is to be separated from its application, a value of the pressure should be adopted which is independent of system characteristics.

The calculation of the interrupting capacity of a breaker at pressures other than those for which tests are available, presents a difficult problem. One rule states that any change in the operating pressure from the listed pressure ratings will usually change the kv-a. rating in about the same percentage. An example of this method is given by Mr. Hayes. The data have been rearranged in Table No. 1 and there has been added the maximum safe rupturing capacity of the breaker and the interrupting capacity of the breaker in amperes, both calculated as outlined in the Hayes paper.

TABLE No. 1

Rated pressure	Operating pressure	Nominal rupturing capacity	Maximum safe rupturing capacity	Interrupting capacity at operating pressure
Volts	Volts	Kv-a.	Kv-a.	Amperes
22,000	22,000	10,000	62,500	1,700
22,000	16,500	12,000	75,000	2,600
22,000	13,200	13,000	81,250	3,600
22,000	7,500	17,000	106,000	8,200
22,000	4,500	19,000	118,750	15,000

An examination of the last column of this table indicates that, while current ratings at 13,200 volts and above are logical, those at 7500 volts and 4500 volts seem too high. Here it is obvious that the formula only holds to about 50 per cent of the maximum pressure listed. Consequently, in adopting rating standards, it will be necessary to consider the limitations through which the formulas will apply.

In considering the interrupting capacity of an oil circuit breaker, it is necessary to remember the duty to be performed by the device. It is called upon to open an electrical circuit which at any given instant has a definite amount of energy stored in the medium surrounding it. The process of opening the circuit causes a change in the energy storage. Under the usual a-c. circuit conditions, a portion of the stored energy must be dissipated when the breaker is opened, the dissipation taking place partly in the breaker and partly in the resistance of the electrical circuit. Besides, account must be taken of the energy stored in the rotating parts of synchronous machines connected to the circuit, and the energy supplied by the prime movers during the circuit interruption.

The usual method of rating oil circuit breakers, as well as those proposed, take into account only the steady current conditions of the circuit. They usually consider its normal pressure or sometimes the pressure just after the circuit is opened, and the current flowing through the breaker. These factors, however, do not completely account for the energy to be dissipated by the breaker. It is, therefore, necessary, in addition, to consider the condition of the circuit immediately preceding an attempt to to open it and the power factor of the circuit during the attempt. In other words, any definition of the duty to be performed by an oil circuit breaker or the rating of its interrupting capacity should include a statement of the power factor on which the rating is based, the point of the current wave at which the arc is started, and other essential factors. The worst conditions of power factor and point of the current wave at which the arc is started should always be understood or defined.

N. L. Pollard: In my opinion confusion will be avoided if all circuit breakers are given either a kv-a. or ampere-volt rating.

Mr. Hewlett stated that it might be necessary to rate a certain capacity of breaker, used a great deal in factories, in kilowatts, as this method of rating would be better understood by the users. If this is done, it may simplify matters for a certain class of users, but it certainly will complicate them for all others. Any purchaser knows the voltage of his system and what load in amperes he expects to carry, therefore he should have no difficulty in choosing the proper breaker. In case he is not satisfied with his own judgment, he should get in touch with some engineer who is competent to advise him.

I have known of cases where the manufacturer of breakers was advised by the purchaser that his load was such that he never would have more than a certain generator capacity connected to his lines at any time, and the manufacturer recommended a breaker which in his opinion would be adapted for the service. Some time later additional generator capacity was installed and several of the breakers failed. Cases like this will always exist unless all users of breakers become competent engineers.

In regard to just what a breaker should do, the question has been raised as to whether it should rupture the circuit only once or several times, with or without putting itself out of commission. There are not many central station men who care to see their station walls and floor splashed with oil or have the switch disabled to the extent that it becomes necessary to put the feeder out of service while repairs to the switch are being made.

In trying to analyze the proper rupturing capacity of a breaker, we come back to the question as to what is meant by "distress". It might be considered to be in distress when a small quantity of oil is thrown out or the contacts are slightly burned. These indications would show that the limit of its capacity had about been reached.

The capacity of the breaker should be great enough to rupture the circuit at least three times without any appreciable quantity of oil being thrown out and without any damage to the switch.

George A. Burnham: The Standards Committee on Switching Equipment had hoped at this meeting to remove one of the apparent obstacles in our way, namely, that of determining a satisfactory method of rating the rupturing capacity of oil switches and circuit breakers.

From the manufacturer's standpoint, it is evident that we are really getting closer to a common basis or rating.

Both Mr. Hayes and Mr. Hewlett are, evidently, in accord as to the method of rating circuit breakers, and this method, if I interpret it correctly, is exactly in accord with the method of rating oil circuit breakers which I presented to the Institute at the mid-winter convention in 1913.

The next important matter, it seems to me, is to select the proper terms to express the method. I do not, however, believe that it is for the best interests of all to include the word "arc" in the phrase which is to express the rupturing capacity of the switch or circuit breaker, for the reason that if we speak of the amperes at the arc it may lead one to believe that we are talking about the potential at the arc as well. Neither do I believe that we should speak of the voltage immediately after or during the time that circuit interruption takes place. For instance, suppose that we have a circuit breaker that is to interrupt a specific amount of current and that the working voltage of the circuit to which it is connected is 15,000 volts. Assume that at the instant the contacts part the voltage on the particular branch of the system which was short-circuited was caused to drop to 13,000 volts at the terminal of the circuit breaker. Now, how shall we rate the circuit breaker with reference to rupturing capacity, on 13,000 volts or on 15,000 volts? It is apparent that there is a possibility for a misunderstanding, which I do not believe should exist.

We all realize that the power factor as well as unsymmetrical current wave form, surges, etc., affect the rupturing capacity of the circuit breaker, but I do believe it would lead to needless confusion in bringing all these factors into consideration by attempting to express the duty of the circuit breaker under the average working condition.

It appears to me that the method of expressing rupturing capacity of a circuit breaker which is at the present time incorporated in the Standardization Rules is very clear and definite, in that it states amperes per phase at normal working voltage.

Mr. Hayes has very aptly put the question before us when he says it is a question of viewpoint. We know that at the present time we cannot say exactly what the switch will do under all possible conditions, but we can say that a circuit breaker is guaranteed to open, say, 6000 amperes at 2500 volts, based on actual test experience, and be assured that it will perform its function properly unless it is working under very special conditions.

There seems to be a difference of opinion as to what constitutes failure in an oil circuit breaker. I, personally, believe that a circuit breaker should be capable of going back into service after it has performed its function under its guaranteed limit. The question as to the number of times is worthy of consideration.

There is no reason but what more simple and direct terms may be used to express what we mean in reference to these matters, and the quicker we do away with the frills the quicker and easier will it be for us to get down to a more comprehensive basis, that we may all understand.

There is another matter which is, perhaps, trifling, but in working out the size of a breaker for a given system we usually arrive at the amount of current which the breaker is called upon to open under certain voltage conditions, and it would be very much easier to select the switch by consulting a table of the amperes per phase at normal working voltage which the various circuit breakers will satisfactorily open, than to attempt to select it from the ultimate kv-a. or bus-capacity basis.

John L. Harper: Our method of deciding on an oil switch at Niagara is to give the company that is used to building them a statement of our conditions, or get them to investigate for themselves; and then to install apparatus, that, when we put the plant back of it, will rupture properly under any duty put upon it.

However, there seems to be two classes of customers to consider—those who wish to get the switch that will just do the work and no more, and the other class, who are very desirous of getting a breaker that will always open and always be ready to go back into service, regardless of its cost and the possibility of having too large an instrument. Therefore, I would be in favor, in rating a circuit breaker, of using—referring to the illustration used by Mr. Burnham—15,000 volts as the maximum working pressure, and disregarding the lowering of the voltage at such time as the breaker may act, and in this way getting a breaker that will be sufficiently large to open under the very worst conditions, although possibly imposing a little upon the party who wishes to cut down the cost and the size of his breaker. I believe that that class of customers should be imposed upon by manufacturers, rather than those who desire and depend upon continuous and successful operation.

H. W. Buck: There was one point touched upon by Mr. Burnham that I should like to amplify, and that is the question of what determines the successful operation of an oil switch. I, myself, have seen oil switches operate under all kinds of conditions, and I never have yet seen one fail to open the circuit—but they have done so at times at the expense of their own existence—and that is the question. Does the rating of an oil switch mean that it is going to open the circuit successfully at that rating, or does it mean that it can only open it with resulting destruction to itself? Between those two limits, there are all degrees of operation.

An oil switch, to successfully operate, within its rating should certainly be able to open a short circuit in such a way that it can immediately go back into service. If it is going to open the circuit and clear a short on the line, and at the same time blow up its tank and throw oil all over the station, that certainly should not be considered to come within its rating. I think that the successful opening of a circuit should be more clearly defined than it is at the present time.

John B. Taylor: There is at least a tendency to come to some kind of an agreement on this question of rating, since both of the authors want to deal in current and voltage, though there seems to be unnecessary confusion as to what particular current is to be taken, and what particular voltage is to be taken. The principal difference is that Mr. Hayes wants to measure the voltage, not of the system before the trouble began, not of the system at some point while the trouble is on, but some final voltage which is not at all definitely defined. I hope that he will explain that a little more clearly. It is quite obvious from the oscillograph record exhibited, that there are a great many currents and a great many voltage values which may be picked off of the record between the time that the trouble begins and the time that the trouble is definitely over.

My own feeling on this question of rating is, that there is bound to be a great deal of difference of opinion and not much headway made, until the theory of the switch is discussed and a better agreement reached as to how the switch works. Now, while Mr. Hayes disclaims any intention of discussing the theory, scattered through the paper here and there, are various observations on how a switch is designed and the factors making one switch more effective than another. The reason why I feel that the theory of the switch is essential to progress, not only on rating, but for developing switches for more extreme service, comes from reviewing the discussions that have been held on this oil switch matter in the Institute papers for the last 10 or 15 years. Two men will think they are discussing the same point, when they are not discussing the same thing at all. The design of the switch—the designers' working theory as to what factors make a switch effective—appears to be in a very hazy state. On the one hand, we have men talking about a vacuum close to the point of the arc, due to the fact that a solid body has been drawn out of the oil leaving a space which the oil must fill; and at the same time the same man will be showing records of pressure up to 50 or 100 pounds to the square inch.

As Mr. Hewlett has pointed out in his paper, the test of switches under extreme duty is almost impossible today. The expense, the trouble and the danger from interrupting the service on large working systems make the opportunity for those tests so few and far between, that the best that any designer can expect to get out of them is a line on the particular switch that he had there. If he has an opportunity to make several short circuits he may be able to see which one is the better, but such tests cannot be done day after day. The minor details of design, that make the difference between success and failure, cannot be fully tried out. Of course, the proof of the pudding is in the eating, and if a switch has been produced that does the work, it may be more or less immaterial whether the details are worked out to the best advantage. In view of the limited opportunities for doing this work, I feel strongly that there is need of designers and investigators stating their ideas of just how a switch behaves and what factors in the design of one switch make it work better than another switch. After there is some semblance of an agreement on these points, the question of rating will be easier.

K. C. Randall: Some years ago transformers were built or designed by comparison, but they are now, built absolutely scientifically. That is, there is a limited amount of iron, a limited amount of copper, and a limited amount of insulation, which are necessary to the production of a certain performance. There is a mathematical calculation that takes care of it, and that is similarly true with induction motors, and more or less with other machinery. For circuit breakers, no such data are known. Circuit breakers are still comparatively built, and they are not designed on a technical basis.

We know how to build breakers that will perform a certain function; but it is possible, even probable, that the breakers that we are building today will be much more cumbersome, heavier, more expensive, than the breakers which we will build when we know something about breakers—I mean analytically. We know that an inductive circuit is more difficult to open than a like non-inductive circuit. But I don't know that any one will volunteer what the difference is? Whether a power factor of 60 per cent, 50 per cent or 10 per cent, bears a definite relation to the difficulty of the circuit-breaker problem. The technical analysis—the study—the real knowledge of the problem—has not been acquired at all.

Specifically, we don't know whether a tank that is 4 feet (121.9 cm.) deep, as against one that is 2 feet (60.9 cm.) deep, will handle twice as much current—will interrupt a circuit of twice the voltage—or will handle twice the kv-a.; nor do we know whether the diameter of the tank—holding the depth the same—if doubled, will double the capacity of the rupturing ability. Now, if these conditions prevail—and I think those who are confronted with applying circuit breakers and designing them and building them agree—then we are not quite ready to finally say just what a rating of a circuit breaker shall be in terms of power factor, current and voltage.

It might be well, then, to suggest that for the time being we should stick to the one question. For a long time we have gone along with a very hit or miss, perhaps antagonistic, lot of local and almost individual methods of rating. If we should agree now to rate breakers by the current, as Mr. Burnham said—not in the arc, but simply in the circuit; and the voltage of the circuit, the normal, operating potential—we will, I believe, obtain a practical working method which will be good for awhile, and will give an effective basis of comparison. Later on, when real knowledge of the problem has been acquired, we can, if desirable—and I frankly doubt whether it will be desirable—introduce the question of power factor.

It has already been said that probably the power factor, under the average condition of severe duty—say short circuit—may average fairly uniform; and if we build breakers which will deal with those fairly uniform conditions, we will solve the problem.

Then comes a matter that has been touched on several times, which I call the "*relation of freedom of distress to maximum rupturing ability or rating.*" A few of these points are: A function of safety; an indication of an available margin for additional duty; matter of appearance and orderliness; a source of security and confidence of the operators, where there is freedom from distress. Smoke and oil throwing are not necessarily proof of a near approach to the maximum rupturing capacity of the breaker; but, with all adjustments right, and with the operation as intended, such demonstrations should, at least, be rare.

Mr. Pollard, I believe, said that if you wanted to have an immaculate station—and I should think most operators would choose that, if it could be obtained at a reasonable expense—a larger unit could be purchased, which would withstand the duty, and not make a demonstration which a smaller and cheaper unit would manifest. So that, after all, whether the unit shall go back into operation clean, unsoiled and noiseless, or whether it shall go back limping, or perhaps having sacrificed itself and really not go back at all, is a matter for the purchaser. The manufacturer is glad to build whatever the purchaser chooses to buy, usually; but, as Mr. Pollard said, it is up to the purchaser, who does the applying to decide what he wants. He can buy a small breaker and blow it up, or he can buy a large one and not blow it up.

The choice of breaker equipment for freedom from demonstration demands the same foresight into the future methods of operation from the operator as he looks forward to his growing loads, that is exercised when he purchases additional generating equipment.

H. W. Buck: For a common kilowatt rating and a common power house capacity back of the arc, the oil switch of course may have to meet the condition either of large current and low voltage, or small current and high voltage.

The plant at Niagara Falls is particularly well equipped to make this direct comparison, in that it has a large plant, operating at 2200 volts, and also another large plant feeding a high-tension line, with the same amount of power back of the short circuits, operating at 60,000 volts. I would like to ask of Mr. Imlay, whether he considers rupturing the low voltage and large current more severe on oil switches than the same kilowatts output at high voltage on small current?

L. E. Imlay: We have very much less difficulty in rupturing the arcs on the high-voltage circuits than on the low voltage.

C. A. Adams: I should like to ask, then, why it is ordinarily considered that at the lower voltages the kv-a. rupturing capacity is larger than at the high voltages?

E. M. Hewlett: In this particular case, Mr. Imlay is not comparing the same switches. He is comparing the small low-voltage switch, which is insulated for a low voltage, with the large high-voltage switch which is insulated for a high voltage.

The low-voltage switch is relatively smaller because it is not necessary to make it larger, the striking distance is not the limiting feature. Hence the high-voltage switch has a great deal more oil in it, is a larger device, and has a higher rupturing capacity.

S. Q. Hayes: I think there is one other point which might be brought out right here. At the higher voltage there is probably more reactance in the circuit, and the amount of power at the arc is probably somewhat less at the higher voltage than at the lower voltage.

H. R. Summerhayes: It seems to me, on that same point, that there is another thing that should be considered. On the high-voltage switch you are not limited in space, and not so strictly limited in investment, as the low-voltage switch. If the manufacturer were allowed to build a low-voltage switch, using the same space and the same investment as is used for the high-voltage switch, he could probably build a switch which would show a very favorable and remarkable performance. The design of the low-voltage switch has been based on investment considerations and space considerations. The low-voltage stations—the large low-voltage stations—at first were always located in large cities, where real estate was expensive and the switches had to be confined to the least space. A great many switches required a great many feeders out of the stations, so that space was a limiting factor. The high-tension switches, on the other hand, are generally, nowadays, put out of doors, and there is no such objection to the large quantities of oil as was encountered in the original designs of low-voltage switches.

Mr. Hayes speaks of rating the switch on the circuit voltage immediately after the short circuit. The question of the meaning of the word *immediately* comes in. Of course we understand that if the field of the generator is under the control of an automatic regulator which pushes up the field excitation as soon as a short circuit comes, then the voltage may rise to a very high point after the short circuit, but that takes time. I can understand that the current is going up, possibly, during the short circuit, but it seems to me that the voltage would not rise until after the switch had opened. On this very point it has been observed that what we might call a sustained short circuit is more difficult to open than one in which the voltage is not sustained.

I am in favor of rating switches on the current which the switch opens and the system voltage. One reason for that is, that nearly all devices used on constant potential systems are rated at the system voltage, and it would be very convenient for engineers to observe the same custom in rating switches, rather than to rate them on a voltage which may be different for every short circuit.

Mr. Hayes speaks of short circuits not occurring closer together than two minutes, the breaker being capable of opening the short circuit ten times within the course of an hour. It occurs to me that such an arbitrary rating would be rather difficult for an operating engineer to take care of in his system. That is, it would be rather difficult to design a railway system, or any other system, in such a way that short circuits would come no closer than two minutes apart. They are not under control.

The point that a switch should be guaranteed to open the circuit, and then be in condition to be re-closed, is one which is well taken. There is very little doubt that most operating engineers prefer to have the switch capable of being reclosed at least once. That, I think, should be a standard. As to the number of times, there may be a difference of opinion, and more investment may be required.

The rating in which the kv-a. capacity goes up in greater proportion than the voltage goes down, is rather difficult to understand, and is rather difficult to reconcile with the other statement in the paper, that the rupturing capacity is a function of the tank dimensions.

There is another point that might be raised, and that is, that different designs of circuit breakers may require different formulas to be applied for the difference in rupturing capacity when the voltage is varied. I think some of them would act differently, on that point.

P. M. Lincoln: It seems to me that the main question under discussion here might be almost called one of the proper selection of a name by which to call our circuit breakers. At the present time, and during the past, if we wanted, for instance, to get a circuit breaker for a 1000-kw. machine, we took its ampere capacity from that of the machine and then selected our breaker on the basis of the short-circuit ampere capacity. Thus for various conditions we had to select various breakers, depending upon the conditions under which they were to be used.

A 1000-kw. machine, if built upon the old specifications when regulation was the thing which was desired in generators above everything else, might be capable of giving 15, 20, 30 times or perhaps even a higher percentage, of its normal current upon short circuit. Under modern conditions, however, particularly since the practise has arisen of using reactances, in series with generators, instead of giving 20, 30 or may be 40 times normal current, the modern generator may only give five to ten times normal full-load current on short circuits; so that, that condition introduces a decided factor in the selection of the breaker.

The question, therefore, is, in the future shall we select our breakers in regard to the normal current which they have to carry, or shall we select the breaker with regard to the maximum overloading—the worst condition that it must carry? I quite agree with both authors. Both authors take the position that the breaker should be selected, and it should be given a name with respect to the maximum short circuit that it has to interrupt. I quite agree with that view.

Some exception has been taken to the language of Mr. Hayes, when he speaks of the voltage to be interrupted. He calls the voltage that which exists immediately after the short circuit has been interrupted. I think Mr. Hayes used that language to give a picture of what the breaker has to do during the process rather than with a view of determining the voltage of the rating. I believe that the proper voltage to be used in getting at this rating is the normal voltage of the circuit.

It seems, therefore, that the main question that we have under discussion in this session is the proper name to apply to breakers, and I quite agree with both of these authors, in feeling that the proper name to give to them is the final rupturing capacity, rather than the normal ampere carrying capacity. Of course the breakers must have that normal ampere carrying capacity—that goes without saying. But the name to call them by should be their maximum rupturing capacity, rather than their normal ampere carrying capacity.

L. W. Chubb: The electromagnetic energy stored in a system when the breaker opens has to be dissipated either as heat in the breaker arc or stored as an electrostatic charge in the system, to be subsequently dissipated by oscillation and absorption in resistance. There are several different things to consider in the breaking of a circuit. The energy put in the breaker tank is a function of the power factor, the time of operation and the phase of the current at the first of the separation. If the breaker opens quickly at the zero point of current the breaker has no work to do and the energy will all go to increasing the voltage of the system. If the breaker takes a long time to open, the stored energy of the system and more coming from the generating station will be dissipated in the arc of the breaker. So that the time and speed of operation, the power factor, the ratio of line capacitance to inductance, and the kind of inductance are all things to be considered. It makes a difference whether the interruption and short circuit are at the far end of the line or near the station. A breaker in the station should handle a short circuit near the station, in which case there is the greatest current, lowest power factor, and lowest ratio of capacitance to inductance. With this low ratio of capacitance there is not the advantage of line elasticity, no place to store the energy, there is an almost instantaneous rise of voltage each time the current pauses at the zero point, which lights the arc repeatedly and the dynamic and stored energy must be taken care of in the arc under oil until the final break. Therefore it seems that to take care of the worst conditions, the rating of breakers should assume a zero power factor.

C. A. Adams: My interest in this subject is largely from the standpoint of standardization, to the end that the rating of an oil switch or circuit breaker may be definite, clear cut and determinable. In the early days of dynamo machinery, the maker's rating frequently differed from what we now understand as the continuous rating, by as much as 50 per cent. (usually in excess), due partly to crudeness in methods of design and calculation, partly to lack of digested experience, partly to lack of knowledge of the qualities of the materials employed, partly to the differing factors of safety employed by the various manufacturers, and partly to the differing allowances which the manufacturers made for the crudeness of the customer's estimate of the capacity required.

We are now in a somewhat similar stage of evolution as regards the rating of oil circuit breakers. The customer does not know exactly the work which the breaker will be called upon to do; the designer does not know how to design, with any reasonable degree of accuracy, a breaker to do just the work specified; and finally the manufacturer cannot easily reproduce the specified conditions of operation, to test his product.

Thus the task before us is two-fold: First, to reduce our knowledge of this whole subject to a more definite, computable and testable basis; and second, to agree upon certain definitions as to rating, etc., so that we will be talking the same language, so that both specifications and bids will be rational and comparable.

Out of the present discussion, one conclusion stands forth clearly in my mind, namely that the rating of an oil circuit breaker should be defined in terms of the work it can safely do, without reference to the nature or capacity of the system to which it may be connected by a particular customer. It is for the customer or his engineer to say what work it will be called upon to do, or to choose a standard breaker with a sufficient margin to cover his maximum requirement. If he wishes an unusually large factor of safety it is for him to specify the correspondingly larger standard rating, as he is the one to pay for this extra insurance.

Finally the task under discussion is not a small or unimportant one, and anyone who contributes even in part to its satisfactory completion deserves a large share of credit and appreciation from the profession at large.

S. Q. Hayes: Referring to Mr. Lichtenberg's discussion. My paper, as stated, is largely a series of disconnected notes. It really does not lay much claim to clearness of definition as to the proper method of this rating. I think probably the fourth line of the summary gives the gist of my idea in preparing this paper—that the main object was to open up a discussion; and I think we have opened up a pretty fair discussion on it. Mr. Lichtenberg I believe also brought out the question about the rating of the circuit breaker and the formula from which that is derived. That, as stated in the paper, is the rating assigned to it by the maker or the designer of that particular breaker. The makers have felt that the breaker which really has the 22,000-volt insulation, and the oil and the tanks suitable for that service, will actually open 1700 amperes at 22,000 volts, and will be reoperative after opening such a short circuit. They also claim that that same breaker will actually open 15,000 amperes at

4500 volts, and be immediately reoperative. They have made tests that prove that that particular breaker can fulfill that particular line of ratings. Whether that formula holds true for every particular line of breaker—as Mr. Summerhayes brings out—is another question. But the makers will guarantee that this particular breaker will meet the particular conditions stated.

Mr. Pollard and others brought out the question of rating in kv-a. or amperes and volts, and the question of the voltage immediately after opening the arc. Under normal conditions we actually rate a breaker at the service voltage. I wanted to point out the fact, however, that under the abnormal conditions met in certain cases, where you do have a very large rise in voltage, that the kv-a. rating should be based on the voltage that is practically available for maintaining that arc, namely, the voltage that exists just after the breaker has cleared the circuit.

H. R. Summerhayes: Don't you think it would be better, as a basis of rating, to use the system voltage?

S. Q. Hayes. I think, as a basis for rating, that the system voltage is probably the best way of doing it. This paper of mine is not any attempt to force this method of rating; but my idea was to put up a method of rating, largely as a target, so as to get the ideas of various people on this subject.

I notice that Mr. Pollard agrees with the recommendation, that the manufacturer should give the rating which he assigns to his oil circuit breaker, and the user should decide whether that breaker actually is satisfactory for his conditions.

The question of distress that Mr. Pollard brought out, really is a question for the operating engineers to settle, rather than for the designer to settle.

As Mr. Adams indicated, one thing necessary is to select the proper terms to be used in rating circuit breakers and the proper method of determining whether the circuit breakers have met their guarantees or not. This paper of mine suggests certain terms, not as being the best possible terms to describe what is intended, but as one method of describing them, in order, to give others a chance to suggest better means of expressing what I have attempted to express in this paper.

Now, that point about whether the breaker should be rated at 15,000 volts or 13,000 volts is, to a certain extent, answered by the recommendation of using the voltage that will exist immediately after the breaker has opened the circuit. That very difficulty is indicated on the curve. After opening, the circuit will undoubtedly have gone back to 15,000 volts, and may be a trifle higher.

Mr. Harper brought out the point that the practise of his company is practically to have the manufacturer send an engineer to investigate the particular conditions and then recommend a breaker that will meet those particular conditions. Now, in plants of the size of Mr. Harper's, that can usually be done; but the idea of this paper was to practically settle on a basis of rating that would take care of probably 90 per cent of the cases. There are undoubtedly other cases—maybe 10 per cent of the whole—where the operator will largely have to depend on the designing engineer—the manufacturing engineer—guaranteeing that he will actually furnish a breaker to meet the particular conditions.

Mr. Harper very aptly brought out the facts that there are two classes of customers. In making a note on Mr. Harper's statement, I called these people "minimum and maximum customers"—one who will be satisfied with the minimum, namely, the cheapest breaker, that will just get away with his service; and, the other one, who wants the best that can be purchased, irrespective of price. Now, naturally the manufacturer would like to see more of that latter class.

Mr. Buck brought out the point of what really was a successful operation; and various other people agreed with Mr. Buck that it was necessary to have repeat operation.

Now, on that oscillogram (referred to by Mr. Taylor), the point that I would take as to the maximum voltage just after opening is the point which is marked on the oscillogram "short circuit opened." You will notice that on this particular system, where this test was made, that point is just slightly above the normal station voltage.

Mr. Taylor brought out the point that testing under actual conditions is almost impossible. As a general rule, that statement is entirely correct. There are a certain number of tests that have been made on plants of comparatively large capacity, so that the operators know, or can know, that the manufacturers really have some actual data on which their apparatus is based.

Mr. Randall brought out the point that circuit breakers are what he called "comparatively built," and "comparatively designed," and that no real analysis has been made of a circuit-breaker design, and that no actual data have been obtained as to the effect of changes in dimensions. Now, those statements are entirely correct. No definite data have been secured as to the effect of increase in dimensions; but a certain amount of comparative data have been available. It is known that a certain type of breaker, with a tank of a certain diameter, will do a certain amount of work, and that the same general design of breaker, with a larger tank, will open a greater amount of power.

Mr. Randall also agreed with the statement made by various speakers, that the current of the circuit to be opened really should be the current at the normal voltage, and not the current that would exist after opening the arc. And he also brought out the various features that would occur at the time of rupture, which he spoke of as "demonstrations."

Mr. Imlay stated that he has found there is less difficulty opening a certain station capacity at 60,000 volts than at 2200 volts. In answering that point at that time I practically asked Mr. Imlay another question, and that was whether at 60,000 volts there really was not more reactance in his circuit, so that the power at the arc really was less on the 60,000 than on the 2200-volt circuit. Now, Mr. Summerhayes and Mr. Hewlett practically brought out, in answer to Mr. Imlay's point, that for the higher voltage, space and price were minor considerations. So that it is undoubtedly true that the high-voltage breakers, which Mr. Imlay has in his plant, open their circuits with less fuss than the low-voltage breaker.

Mr. Imlay I believe also brought out the question of the rating of the low-voltage breaker—the rating of a breaker being given greater for low voltage than for high voltage. I answered that question earlier, to the effect that those are the ratings which the manufacturer of that breaker guarantees the breaker will meet.

Mr. Summerhayes brought out the point that the space and the price of a low-voltage breaker, particularly when installed in city plants, where real estate was of vast importance, was one of the limiting features on the low-voltage breaker that was not met with in the high-voltage breaker; and that given more or less unlimited space and more or less unlimited price the low-voltage breaker could be made to open the circuit just as readily as the high-voltage breaker.

Mr. Summerhayes also stated that, it is his recommendation that the current rating should be on the system voltage. I practically agree with him; but I have brought out the point that for those particular conditions where we did have a high rise in voltage after an arc, that it will have to be watched rather carefully. Now, just on that point, there is one feature of circuit-breaker operation that some people lose sight of, and that is, that if you have a number of parallel connected circuits and one of them is opened due to a short circuit on that particular feeder, the duty is less on that breaker, because the system can discharge over the other circuits, than if that were the only circuit and it had to open all of the stored magnetic energy of the system.

Mr. Lincoln brought out the fact that the real feature was the proper selection of the name to be assigned to a circuit-breaker rating. And Mr. Lincoln stated correctly my viewpoint on that question of the open-circuit voltage that took place immediately after the breaker opened.

Mr. Chubb brought out the point of the energy to open and the storage of energy, and the point that I just made, about circuit breakers and parallel circuits, takes care of that point.

Mr. Adams felt that the rating of the breaker should be practically independent of the system; and, if it is possible to do so, I feel that that is the proper method of rating.

E. M. Hewlett: In reference to Mr. Pollard's point, and as Mr. Hayes stated, the manufacturer would like to have only one rating, and that rating for safety and service. Unfortunately, there are two classes of customers. Some want all they can get and others are content with just enough to squeeze through. You must consider both parties in the designing and the rating, so that you will need a rating that can be used both ways, or let a different safety factor be taken by the man who is willing to take the risk.

Mr. Randall is quite right in reference to our data. We have a great deal comparing different capacities and different dimensions, and the service that the switches have given will bear out the way we have used that data. I think that the manufacturers have selected ratings that have given on the average, very good service.

Mr. Lincoln spoke of using the rating—that is, the rupturing capacity rating—as the rating of the switch. I think, however, that a switch needs a first and a last name, as well as some other features, and that you have to give it not only a rupturing rating, but also a normal current carrying capacity at the station voltage.

Then, to take up the last point, the rupturing capacity should be stated in the actual current that the switch is called upon to open at the operating voltage. There are a great many factors, you can see, that have to be brought in; but we can use such a rating as this until such time as we find we have sufficient data to formulate a new rating.

P. Lindemann (by letter): It is quite evident that we will have as many types of circuit breakers as we have types of apparatus or systems to be protected.

Taking into consideration our present method of rating generators, transformers and motors, it seems most preferable that our oil switches or other protecting devices be treated with a like method of rating, so for a generator having a given name plate rating that a similar name plate rating be placed on the oil switch to signify the proper size of switch necessary.

By this method for a transmission line the proper oil switch would be one having a name plate rating equivalent to the current, voltage, frequency and power factor of the line which it is to protect.

Assuming the line connected to generator bus bars, a generator type of switch would be selected and if the switch was to be placed at the far end of the same line with no load taken off between them, the two oil switches should have the same ratings theoretically, their types however would be different.

It seems to me that the possible surges of voltage and current should not enter into its name plate rating, but rather that they be assumed in the design by the manufacturers.

In addition to the above an oil switch of such design as to take care of twelve interruptions of its maximum rating at two minute intervals before inspection is necessary, would be ideal practically.

STANDARDIZATION RULES

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

HISTORY OF THE STANDARDIZATION RULES

The first step taken by the Institute toward the standardization of electrical apparatus and methods was a topical discussion on " The Standardization of Generators, Motors and Transformers," which took place simultaneously in New York and Chicago on the evening of January 26, 1898. The discussion appears in the Institute TRANSACTIONS, Vol. XV, pages 3 to 32. The opinions expressed were generally favorable to the scheme of standardization of electrical apparatus, although some members feared that difficulties might arise. As a result of this discussion, a Committee on Standardization was appointed by the Council of the Institute, consisting of the following members:

FRANCIS B. CROCKER, *Chairman.*
CARY T. HUTCHINSON
ARTHUR E. KENNELLY
JOHN W. LIEB, JR.
CHARLES P. STEINMETZ
LEWIS B. STILLWELL
ELIHU THOMSON

After a careful consideration of the matter and consultation with the members of the Institute and interested parties generally, a " Report of the Committee on Standardization," was presented and accepted by the Institute, June 26, 1899. Those original rules appeared in the Institute TRANSACTIONS, Vol. XVI, pages 255 to 268.

As a result of changes and developments in the electric art, it was subsequently found necessary to revise the original report, this work being carried out by the following Committe on Standardization:

FRANCIS B. CROCKER, *Chairman.*
ARTHUR E. KENNELLY
JOHN W. LIEB, JR.
C. O. MAILLOUX
CHARLES P. STEINMETZ
LEWIS B. STILLWELL
ELIHU THOMSON

This revised report was adopted at the 19th Annual Convention at Great Barrington, Mass., on June 20, 1902, and appears in the Institute TRANSACTIONS, Vol. XIX, pages 1075 to 1092.

In consequence of still further change and development in electrical apparatus and methods, it was decided in September, 1905, that a second revision was needed, and the following Committee was appointed to do this work.

FRANCIS B. CROCKER, *Chairman.*
ARTHUR E. KENNELLY, *Secretary.*
HENRY S. CARHART
JOHN W. LIEB, JR.
C. O. MAILLOUX
ROBERT B. OWENS
CHARLES F. SCOTT
CHARLES P. STEINMETZ
HENRY G. STOTT
S. W. STRATTON

This Committee held monthly meetings and carried on extensive correspondence with manufacturers, consulting and operating engineers and other interested parties, and as a result, presented its report at the 23d Annual Convention, held at Milwaukee, May 28–30, 1906. After considerable discussion the report was accepted and referred back to the Committee for amendment and rearrangement in form. It was then to be submitted to the Board of Directors for final adoption. In September, 1906, the following Standardization Committee was appointed:

FRANCIS B. CROCKER, *Chairman.*
ARTHUR E. KENNELLY, *Secretary.*
A. W. BERRESFORD
DUGALD C. JACKSON
C. O. MAILLOUX
ROBERT B. OWENS
CHARLES F. SCOTT
CHARLES P. STEINMETZ
HENRY G. STOTT
S. W. STRATTON
ELIHU THOMSON

This Committee held monthly meetings, also sub-committee meetings, and carefully referred the rules as a whole, and each part of them, to the members of the Institute. The rules were also entirely rearranged as to form, and put in shape to facilitate ready reference to them and enable future revisions to be made without breaking up the logical arrangement. Thus amended the rules were submitted to the Board of Directors and approved by it on June 21, 1907. The Board also directed that the rules should be presented, as accepted by the Board, at the Annual Convention held at Niagara Falls, June 24 to 27, 1907, which action was taken by President Sheldon on June 26, 1907. By the Constitution which went into effect on June 10, 1907, this Committee has been made a standing Committee with the title "Standards Committee," consisting of nine members.

On August 12, 1910, the Board of Directors increased the size of the committee from nine to twelve members; on October 14 from twelve to fourteen, and on March 10, 1911, from fourteen to sixteen. The committee thus constituted is given below.

COMFORT A. ADAMS, *Chairman.*
ARTHUR E. KENNELLY, *Secretary.*
H. W. BUCK
GANO DUNN
H. W. FISHER
H. B. GEAR
J. P. JACKSON
W. L. MERRILL
RALPH D. MERSHON
W. S. MOODY
R. A. PHILIP
W. H. POWELL
CHARLES ROBBINS
E. B. ROSA
CHARLES P. STEINMETZ
CALVERT TOWNLEY

This committee and several sub-committees held numerous meetings at which the general revision of the Standardization Rules of the Institute was considered. The complete Standardization Rules, as revised by this committee, were presented to and approved by the Board of Directors on June 27, 1911, at the Annual Convention held at Chicago, Ill.

During the following two years (1911-1913) the Standards Committee, somewhat modified and enlarged, undertook a radical revision of the Rules, particularly in connection with the important subject of Rating. In August 1913 the Committee was still further enlarged by the Board of Directors in order to permit of comprehensive sub-committees for the various parts of the work. The Committee thus constituted is given as follows:

A. E. Kennelly, *Chairman.*
Comfort A. Adams, *Secretary.*

SUB-COMMITTEE No. 1. ON RATING.

H. M. Hobart, *Chairman.*

James Burke
W. C. L. Eglin
B. G. Lamme
W. A. Layman
W. L. Merrill
W. S. Moody
W. H. Powell
Charles Robbins
C. F. Scott
James M. Smith
Charles P. Steinmetz
J. Franklin Stevens
Philip Torchio

SUB-COMMITTEE No. 2. ON TELEGRAPH AND TELEPHONE STANDARDS.

F. B. Jewett, *Chairman.*

H. W. Fisher
F. F. Fowle
R. H. Marriott
J. H. Morecroft
J. M. Smith

SUB-COMMITTEE No. 3. ON RAILWAY STANDARDS.

W. A. Del Mar, *Chairman.*

F. W. Carter*
Hugh Hazelton*
E. R. Hill*
H. M. Hobart
William McClellan
Harold Pender
Martin Schreiber*
N. W. Storer*

SUB-COMMITTEE No. 4. ON NOMENCLATURE AND SYMBOLS.

Comfort A. Adams, *Chairman.*

Louis Bell
Dugald C. Jackson
M. G. Lloyd
H. Pender
E. B. Rosa
A. S. McAllister
R. H. Marriott

SUB-COMMITTEE No. 5. ON WIRES AND CABLES.

H. W. Fisher, *Chairman.*

Wallace Clark
W. A. Del Mar
W. C. L. Eglin
E. B. Rosa
C. E. Skinner
S. W. Stratton

SUB-COMMITTEE NO. 6. ON RATING AND TESTING OF CONTROL APPARATUS.

L. T. Robinson, *Chairman.*

Morton Arendt
N. A. Carle
C. H. Sharp
P. H. Thomas
Philip Torchio

Sub-committee No. 1 had representation from the National Electric Light Association (Messrs. L. L. Elden, G. L. Knight, J. E. Kearns, and E. P. Dillon), from the Association of Edison Illuminating Companies (Mr. P. Torchio) and from the Electric Power Club (Messrs. James Burke and J. M. Smith).

Sub-committee No. 3, through Messrs. Schreiber and Del Mar, respectively, worked in collaboration with the Committees of the American Electric Railway Engineering Association, and the Association of Railway Electrical Engineers.

*Sub-committee No. 3 was a joint subcommittee of the Standards Committee and of the Railway Committee. The members opposite whose names occurs an asterisk, represented the latter committee.

The following members, although not appointed on the Standards Committee, have materially contributed to its work and have attended its meetings:

Carl J. Fechheimer, E. D. Priest, R. B. Williamson, K. A. Pauly, L. F. Blume, C. Renshaw, G. H. Hill, C. J. Hixson.

The radical revision begun in 1911 was completed by this Committee and approved by the Board of Directors at a special meeting held on July 10, 1914, subject to editorial revision by the Committee, and to go into force on Dec. 1, 1914.

The Committee of 1914-1915 which carried out the editorial revision, found it impossible to complete the work satisfactorily by Dec. 1st. The edition of July 1st, 1915, approved by the Board of Directors at its meeting of June 30, 1915, thus represents substantially the completion and clarification of the previous radical revision, although it includes a number of important additions. This Committee was constituted as follows:

A. E. KENNELLY, Chairman, Harvard University, Cambridge, Mass.
C. A. ADAMS, Secretary, Harvard University, Cambridge, Mass.
JAMES BURKE, Erie, Pa.
W. A. DEL MAR, New York.
H. W. FISHER, Perth Amboy, N. J.
G. L. KNIGHT, Brooklyn, N. Y.
H. M. HOBART, Schenectady, N. Y.
F. B. JEWETT, New York.
P. JUNKERSFELD, Chicago, Ill.
W. L. MERRILL, Schenectady, N. Y.
W. H. POWELL, Milwaukee, Wis.
CHARLES ROBBINS, East Pittsburgh, Pa.
L. T. ROBINSON, Schenectady, N. Y.
E. B. ROSA, Washington, D. C.
C. E. SKINNER, East Pittsburgh, Pa.
J. M. SMITH, New York.
H. G. STOTT, New York.
P. H. THOMAS, New York.

During 1915-16 a number of changes, deletions and additions were made. The 1915-16 Committee was constituted as follows:

C. A. ADAMS, Chairman, Harvard University, Cambridge, Mass.
HAROLD PENDER, Secretary, Univ. of Pennsylvania, Philadelphia, Pa.
FREDERICK BEDELL,
L. F. BLUME,
JAMES BURKE,
N. A. CARLE,
E. J. CHENEY,
FRANK P. COX,
W. A. DEL MAR,
W. F. DURAND,
H. W. FISHER,
H. M. HOBART,
F. B. JEWETT,
P. JUNKERSFELD,
A. E. KENNELLY,
G. L. KNIGHT,
A. S. McALLISTER,
W. M. McCONAHEY,
W. L. MERRILL,
R. B. OWENS,
CHARLES ROBBINS,
L. T. ROBINSON,
E. B. ROSA,
C. E. SKINNER,
H. G. STOTT.

In addition to the members of the Standards Committee, the following members of the Institute have served on one or more of the various subcommittees: J. R. C. Armstrong, H. S. Baldwin, Joseph Bijur, G. A. Burnham, W. S. Clark, L. W. Chubb, F. M. Farmer, G. M. W. Goettling, J. D. Harnden, R. E. Hellmund, C. T. Henderson, E. M. Hewlett, Guy Hill, H. D. James, Paul MacGahan, J. N. Mahoney, H. S. Osborne, K. A. Pauly, C. H. Sharp, T. H. Schoepf, P. H. Thomas, Philip Torchio, M. O. Troy, J. L. Woodbridge.

The following societies directly and through the committees named, have given helpful cooperation in the present revision of the Rules:

American Society for Testing Materials,
Committee B-1.

Association of Edison Illuminating Companies,
Committee on Meters.

Illuminating Engineering Society,
Committee on Nomenclature and Standards.

Electric Power Club,
Committee on Engineering Recommendations; Standardization Committee.

National Electric Light Association
Committee on Meters.
Committee on Apparatus.

Association of Railway Electrical Engineers
Committee on Wires and Cables.

American Electric Railway Engineering Association,
Committees on Equipment and Distribution.

Institute of Radio Engineers,
Committee on Standardization.

Society of Automobile Engineers,
Standards Committee

Of particular value in the present revision of the Rules has been the very cordial cooperation of the British Engineering Standards Committee, which was represented at the final meeting of the Standards Committee on May 15 and 16 by its Electrical Secretary, Mr. C. le Maistre, who came from London to New York for this express purpose. The British Engineering Standards Committee is supported by the following British Societies: The Institution of Civil Engineers, the Institution of Mechanical Engineers, The Institution of Naval Architects, The Iron and Steel Institute, The Institution of Electrical Engineers.

In order to crystalize the policy of the Standards Committee in its own activities, and in its relation to similar committees of other engineering societies, the 1915-16 Standards Committee formulated the by-laws given on the next page. These were approved by the Board of Directors June 28, 1916.

NOTE.

The Standards Committee takes this occasion to draw the attention of the membership to the value of suggestions based upon experience gained in the application of the Rules to general practise.

Any suggestions looking toward improvement in the Rules should be communicated to the Secretary of the Institute, for the guidance of the Standards Committee in the preparation of future editions.

BY-LAWS OF THE STANDARDS COMMITTEE OF THE A. I. E. E.

In Section 28 of the By-Laws the duties of the Standards Committee are stated as follows:

" The Standards Committee shall consider and investigate all matters relating to units and standards appertaining to or applicable in electrical engineering and in the allied arts and sciences. The Committee shall make reports and recommendations to the Board of Directors for action thereon."

The following by-laws are in accord with this section of the Constitution.

1 These by-laws, when approved by the Board of Directors, shall supersede all former resolutions governing the action and policy of the Standards Committee.

2 The minutes of each meeting, marked "Not for Publication," shall be sent by the Secretary to each member of the Committee. These minutes shall contain a summary of the reasons presented for and against any amendment or addition to the Standardization Rules which may be discussed at the meeting. An amendment or addition adopted by the Committee shall be marked in the minutes in a distinctive manner.

3 All amendments and additions adopted by the Committee during any fiscal year may be reconsidered by the Committee at any time, and shall be reviewed at its meeting held in May, and only those amendments and additions confirmed at this meeting shall be presented to the Board of Directors for their approval. Three-fourths of the votes of those present and voting shall be necessary for such confirmation. Any objection or change to be considered at this meeting shall be submitted in writing prior to the meeting and no action other than a vote for or against confirmation of any previous action of the Committee shall be taken at this meeting, except upon the unanimous vote of those present.

4 Amendments and additions to the Standardization Rules adopted by the Committee are not in force until approved by the Board of Directors, and may be reconsidered by the Committee at any time.

5 Cooperation is desirable between the Standards Committee of the Institute and other standards committees. To this end, a report, marked " Not For Publication," of the amendments and additions adopted at each meeting of the Committee shall be sent to those standards committees with which cooperation has been established.

6 An objection from a cooperating standards committee to an action taken by this Committee shall be considered at the next meeting of this Committee following the receipt of a written statement of this objection, provided such objection be submitted within thirty days of the date on which was mailed the report of the action to which objection is made.

A notice from another standards committee of a pending objection shall, however, suffice for an extension of time. In the case of foreign standards committees, the time allowed for an objection to be filed may be extended at the option of this Committee.

7 A cooperating standards committee which may submit an objection to a previous action of this Committee shall be invited to send a representative to the meeting or meetings of this Committee at which such objection is scheduled for consideration.

8 Whenever a new edition of the Rules is issued, old Rules in which changes other than typographical corrections have been made, and all additions and deletions, shall be distinctively indicated.

9 Amendments and additions to these By-Laws may be made by this Committee, subject to the approval of the Board of Directors.

OTHER APPROVED STANDARDIZATION RULES

At the April meeting the Standards Committee passed the following resolution, which was approved by the Board of Directors on April 14th:

"The Standards Committee, with the approval of the Board of Directors, recommends the use of the following rules and standards as adopted by other societies. These have been formally presented to the Standards Committee by the societies concerned and are found not to be incompatible with the Standardization Rules."

The Standards Committee will be pleased to receive from any of the engineering societies such standardization rules as they may care to have included in this list. Such rules will be included (by title only) if they are found not to be incompatible with the Standardization Rules of the A. I. E. E.

STANDARDIZATION RULES

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

DEFINITIONS

NOTE. The following definitions are intended to be practically descriptive, rather than scientifically rigid.

CURRENT, E.M.F. and POWER.

(The definitions of currents given below apply also, in most cases, to electromotive force, potential difference, magnetic flux, etc.)

1 **Direct Current.** A unidirectional current. As ordinarily used, the term designates a practically non-pulsating current.

2 **Pulsating Current.** A current which pulsates regularly in magnitude. As ordinarily employed, the term refers to unidirectional current.

3 **Continuous Current.** A practically non-pulsating direct current.

4 **Alternating Current.** A current which alternates regularly in direction. Unless distinctly otherwise specified, the term "alternating current" refers to a periodic current with successive half waves of the same shape and area.

5 **Oscillating Current.** A periodic current whose frequency is determined by the constants of the circuit or circuits.

6 **Cycle.** One complete set of positive and negative values of an alternating current.

7 **Electrical Degree.** The 360th part of a cycle.

8 **Period.** The time required for the current to pass through one cycle.

9 **Frequency.** The number of cycles or periods per second. The product of 2π by the frequency is called the *angular velocity* of the current.

10 **Root-Mean-Square** or **Effective Value.** The square root of the mean of the squares of the instantaneous values for one complete cycle. It is usually abbreviated r.m.s. Unless otherwise specified, the numerical value of an alternating current refers to its r.m.s. value. The r.m.s. value of a sinusoidal wave is equal to its maximum, or crest value, divided by $\sqrt{2}$. The word "virtual" is sometimes used in place of r.m.s., particularly in Great Britain.

11 **Wave-Form** or **Wave-Shape.** The shape of the curve obtained when the instantaneous values of an alternating current are plotted against time in rectangular co-ordinates. The distance along the time axis corresponding to one complete cycle of values is taken as 2π radians, or 360 degrees. Two alternating quantities are said to have the same wave-form when their ordinates of corresponding phase (see § 13) bear a constant ratio to each other. The wave-shape, as thus understood, is therefore independent of the frequency of the current and of the scale to which the curve is plotted.

12 **Simple Alternating** or **Sinusoidal Current**. One whose wave-shape is sinusoidal.

Alternating-current calculations are commonly based upon the assumption of sinusoidal currents and voltages.

13 **Phase.** The distance, usually in angular measure, of the base of any ordinate of an alternating wave from any chosen point on the time axis, is called the phase of this ordinate with respect to this point. In the case of a sinusoidal alternating quantity, the phase at any instant may be represented by the corresponding position of a line or *vector* revolving about a point with such an angular velocity ($\omega = 2\pi f$), that its projection at each instant upon a convenient reference line is proportional to the value of the quantity at that instant.

14 **Non-Sinusoidal Quantities.** Quantities that cannot be represented by vectors of constant length in a plane. The following definitions of phase, active component, reactive component, etc., are not in general applicable thereto. Certain " equivalent " values, as defined below, may, however, be used in many instances, for the purpose of approximate representation and calculation.

15 **Crest-Factor** or **Peak-Factor.** The ratio of the crest or maximum value to the r.m.s. value. The crest factor of a sine-wave is $\sqrt{2}$.

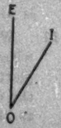
16 **Form Factor.** The ratio of the r.m.s. to the algebraic mean ordinate taken over a half-cycle beginning with the zero value. If the wave passes through zero more than twice during a single cycle, that zero shall be taken which gives the largest algebraic mean for the succeeding half-cycle. The form factor of a sine-wave is 1.11.

17 **The Distortion Factor of a wave.** The ratio of the r.m s. value of the first derivative of the wave with respect to time, to the r.m.s. value of the first derivative of the equivalent sine wave.

18 **Equivalent Sine Wave.** A sine wave which has the same frequency and the same r.m.s. value as the actual wave.

*19 **Phase Difference: Lead and Lag.** When corresponding cyclic values of two sinusoidal alternating quantities of the same frequency occur at different instants, the two quantities are said to differ in phase by the angle between their nearest corresponding values; *e.g.*, the phase angle between their nearest ascending zeros or between their nearest positive maxima. That quantity whose maximum value occurs first in time is said to lead the other, and the latter is said to lag behind the former.

*20 **Counter-Clockwise Convention.** It is recommended that in any vector diagram, the leading vector be drawn counter-clockwise with respect to the lagging vector, † as in the accompanying diagram, where OI represents the vector of a current in a simple alternating-current circuit, lagging behind the vector OE of impressed e.m.f.



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*Note: Definitions 19, 20, 21, 22, 23, 24, 25 refer strictly only to cases where the voltage and current are both sinusoidal (see §11 and 12).

†See Publication of 12 the International Electrotechnical Commission (Report of Turin meeting, Sept. 1911, p. 78).

*21 **The Active or In-Phase Component** of the current in a circuit is that component which is in phase with the voltage across the circuit; similarly the active component of the voltage across a circuit is that component which is in phase with the current. The use of the term *energy component* for this quantity is disapproved.

*22 **Reactive or Quadrature Component** of the current in a circuit. That component which is in quadrature with the voltage across the circuit; similarly, the reactive component of the voltage across the circuit is that component which is in quadrature with the current. The use of the term *wattless component* for this quantity is disapproved.

*23 **Reactive Factor.** The sine of the angular phase difference between voltage and current; *i. e.*, the ratio of the reactive current or voltage to the total current or voltage.

*24 **Reactive Volt-Amperes.** The product of the reactive component of the voltage by the total current, or of the reactive component of the current by the total voltage.

*25 **Non-Inductive Load and Inductive Load.** A *non-inductive* load is a load in which the current is in phase with the voltage across the load. An *inductive* load is a load in which the current lags behind the voltage across the load. A *condensive* or *anti-inductive* load is one in which the current leads the voltage across the load.

26 **Power in an Alternating-Current Circuit.** The average value of the products of the coincident instantaneous values of the current and voltage for a complete cycle, as indicated by a wattmeter.

27 **Volt-Amperes or Apparent Power.** The product of the r.m.s. value of the voltage across a circuit by the r.m.s. value of the current in the circuit. This is ordinarily expressed in kv-a.

28 **Power Factor.** The ratio of the power (cyclic average as defined in §26) to the volt-amperes. In the case of sinusoidal current and voltage, the power factor is equal to the cosine of their difference in phase.

29 **Equivalent Phase Difference.** When the current and e.m.f. in a given circuit are non-sinusoidal, it is customary, for purposes of calculation, to take as the " equivalent " phase difference, the angle whose cosine is the power factor (see §28) of the circuit. There are cases, however, where this equivalent phase difference is misleading, since the presence of harmonics in the voltage wave, current wave, or in both, may reduce the power factor without producing a corresponding displacement of the two wave forms with respect to each other; *e.g.*, the case of an a-c. arc. In such cases, the components of the equivalent sine waves, the equivalent reactive factor and the equivalent reactive volt-amperes may have no physical significance.

30 **Single-Phase.** A term characterizing a circuit energized by a single alternating e.m.f. Such a circuit is usually supplied through

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*Note: Definitions 19, 20, 21, 22, 23, 24, 25 refer strictly only to cases where the voltage and current are both sinusoidal (see §11 and 12).

two wires. The currents in these two wires, counted positively outwards from the source, differ in phase by 180 degrees or a half-cycle.

31 **Three-Phase.** A term characterizing the combination of three circuits energized by alternating e.m.f.'s. which differ in phase by one-third of a cycle; *i.e.*, 120 degrees.

32 **Quarter-Phase, also called Two-Phase.** A term characterizing the combination of two circuits energized by alternating e.m.f's. which differ in phase by a quarter of a cycle; *i.e.*, 90 degrees.

33 **Six-Phase.** A term characterizing the combination of six circuits energized by alternating e.m.f's. which differ in phase by one sixth of a cycle; *i.e.*, 60 degrees.

34 **Polyphase.** A general term applied to any system of more than a single phase. This term is ordinarily applied to symmetrical systems.

Per Cent Drop.

50 In electrical machinery, the ratio of the **internal resistance drop** to the terminal voltage, expressed in per cent, is called the "*per cent resistance drop.*"

51 Similarly the ratio of the **internal reactance drop** to the terminal voltage, expressed in per cent, is called the "*per cent reactance drop.*"

52 Similarly the ratio of the **internal impedance drop** to the terminal voltage, expressed in per cent, is called the "*per cent impedance drop.*"

Unless otherwise specified, these per cent drops shall be referred to rated load and rated power factor.

53 **In the case of transformers,** the per cent drop will be the sum of the primary drop (reduced to secondary turns) and the secondary drop, in per cent of secondary terminal voltage.

54 **In the case of induction motors,** it is advantageous to express the drops in per cent of the internally induced e.m.f.

55 **The Load Factor of a machine, plant or system.** The ratio of the average power to the maximum power during a certain period of time. The average power is taken over a certain period of time, such as a day, a month, or a year, and the maximum is taken as the average over a short interval of the maximum load within that period.

In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load-factor. The proper interval and period are usually dependent upon local conditions and upon the purpose for which the load factor is to be used.

56 **Plant Factor.** The ratio of the average load to the rated capacity of the power plant, *i.e.*, to the aggregate ratings of the generators.

57 **The Demand of an Installation or System** is the load which is drawn from the source of supply at the receiving terminals averaged over a suitable and specified interval of time. Demand is expressed in kilowatts, kilovolt-amperes, amperes,, or other suitable units.

58 **The Maximum Demand of an Installation or System** is the greatest of all the demands which have occurred during a given period.

It is determined by measurement, according to specifications, over a prescribed time interval.

59 **Demand Factor.** The ratio of the maximum demand of any system or part of a system, to the total connected load of the system, or of the part of system under consideration.

60 **Diversity Factor.** The ratio of the sum of the maximum power demands of the subdivisions of any system or parts of a system to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

61 **Connected Load.** The combined continuous rating of all the receiving apparatus on consumers' premises, connected to the system or part of the system under consideration.

62 **The Saturation Factor of a machine.** The ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. Unless otherwise specified, the saturation factor of a machine refers to the no-load excitation required at normal rated speed and voltage. It is determined from measurements of saturation made on open circuit at rated speed.

63 **The Percentage Saturation** of a machine at any excitation may be found from its saturation curve (generated voltage as ordinates, against excitation as abscissas), by drawing a tangent to the curve at the ordinate corresponding to the assigned excitation, and extending the tangent to intercept the axis of ordinates drawn through the origin. The ratio of the intercept on this axis to the ordinate at the assigned excitation, when expressed in percent, is the percentage saturation, and is independent of the scales selected for excitation and voltage. This ratio, as a fraction, is equal to the reciprocal of the saturation-factor at the same excitation, deducted from unity; or, if f be the saturation factor and p the percentage saturation,

$$p = 100\left(1 - \frac{1}{f}\right)$$

64 **Magnetic Degree.** The 360th part of the angle subtended, at the axis of a machine, by a pair of its field poles. One **mechanical degree** is thus equal to as many magnetic degrees as there are pairs of poles in the machine.

65 **The Variation in Prime Movers** which do not give an absolutely uniform rate of rotation or speed, as in reciprocating steam engines, is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution taken as 360 degrees.

66 **The Variation in Alternators** or alternating-current circuits in general, is the maximum angular displacement, expressed in electrical degrees, (one cycle = 360 deg.) of corresponding ordinates of the voltage wave and of a wave of absolutely constant frequency equal to the average frequency of the alternator or circuit in question, and may be due to the variation of the prime mover.

67 **Relations of Variations in Prime Mover and Alternator.** If p is the number of pairs of poles, the variation of an alternator is p times the variation of its prime mover, if direct-connected, and pn times the variation of the prime mover if rigidly connected thereto in such a manner that the angular speed of the alternator is n times that of the prime mover.

68 **The Pulsation in a Prime Mover, or in the alternator connected thereto.** The ratio of the difference between the maximum and minimum velocities in an engine-cycle to the average velocity.

80 **Capacity.** The two different senses in which this word is used sometimes lead to ambiguity. It is therefore recommended that whenever such ambiguity is likely to arise, the descriptive term ***power capacity*** or ***current capacity*** be used, when referring to the power or current which a device can safely carry, and that the term "***Capacitance***" be used when referring to the electrostatic capacity of a device.

81 **Resistor.** A device, heretofore commonly known as a resistance, used for the operation, protection, or control of a circuit or circuits See **§ 740.**

82 **Reactor.** A coil, winding or conductor, heretofore commonly known as a reactance coil or choke coil, possessing inductance, the reactance of which is used for the operation, protection or control of a circuit or circuits. **See also § 214 and 736.**

83 **Efficiency.** The efficiency of an electrical machine or apparatus is the ratio of its useful output to its total input.

TABLE I.

90 Symbols and Abbreviations.

Name of Quantity.	Symbol for the Quantity.	Unit.	Abbreviation for the Unit.
Electromotive force, abbreviated e.m.f.	E, e	volt	....
Potential difference, abbreviated p.d.	V, v or E, e	"	....
Voltage	E, e or V, v	"	....
Current	I, i	ampere	....
Quantity of electricity	Q, q	coulomb, ampere-hour	....
Power	P, p	watt	....
Electrostatic flux	Ψ	....	....
Electrostatic flux density	D	....	....
Electrostatic field intensity	F		
Magnetic flux	Φ, φ	maxwell	....
Magnetic flux density	B, $\mathcal{B}$	gauss	....
Magnetic field intensity	H, $\mathcal{H}$	gilbert per centimeter or gauss†	gilbert per cm. ....

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†The gauss is provisionally accepted for the present as the name of both the unit of field intensity and flux density, on the assumption that permeability is a simple numeric.

Magnetomotive force, abbreviated m.m.f.	$\mathcal{F}$	gilbert*	....
Intensity of magnetization	J	....	....
Susceptibility	$\kappa = J/H$	....	....
Permeability	$\mu = B/H$	....	....
Resistance	R, r	ohm	....
Reactance	X, x	"	....
Impedance	Z, z	"	....
Conductance	g	mho	....
Susceptance	b	"	....
Admittance	Y, y	"	....
Resistivity	ρ	† ohm-centimeter	ohm-cm.
Conductivity	γ	†mho per centimeter	mho per cm.
Dielectric constant	ϵ or k	....	....
Reluctance	$\mathcal{R}$	....	....
Capacitance (Electrostatic capacity)	C	farad	....
Inductance (or coefficient of self induction)	L	henry	....
Mutual Inductance (or coefficient of mutual induction)	M	henry	....
Phase displacement	θ, φ	degree or radian	°
Frequency	f	cycle per second	~
Angular velocity	ω	radian per second	....
Velocity of rotation	n	revolution per second	rev. per sec.
Number of conductors or turns	N	convolution or turns of wire	
Temperature	T, t, θ	degree centigrade	C
Energy, in general	U or W	joule, watt-hour	....
Mechanical work	W or A	joule, watt-hour	....
Efficiency	η	per cent	....
Length	l	centimeter	cm.
Mass	m	gram	g
Time	t	second	sec.

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*An additional unit for m. m. f. is the "ampere-turn," for flux the "line," for magnetic flux-density "maxwells per sq. in."

†*Note.* The numerical values of these quantities are *ohms resistance* and *mhos conductance* between two opposite faces of a cm. cube of the material in question, but the correct names are as given, not ohms and mhos per cm. cube, as commonly stated

Acceleration due to gravity	g	centimeter per second per second	cm. per sec. per sec.
Standard acceleration due to gravity (at about 45 deg. latitude and sea level) equals 980.665†................	g_o	centimeter per second per second	cm .per sec. per sec.

91 E_m, I_m and P_m should be used for maximum cyclic values, e, i and p for instantaneous values, E and I for r.m.s. values (see §10) and P for the average value of the power, or the active power. These distinctions are not necessary in dealing with continuous-current circuits. In print, vector quantities should be represented by boldface capitals.

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†This has been the accepted standard value for many years and was formerly considered to correspond accurately to 45° Latitude and sea level. Later researches, however, have shown that the most reliable value for 45° and sea-level is slightly different; but this does not affect the standard value given above.

CLASSIFICATION OF MACHINERY

100 The machinery under consideration in these rules may be classified in various ways, these various classifications overlapping or interlocking in considerable degree. Briefly, they are Direct-Current or Alternating-Current, Rotating or Stationary. Under Rotating Apparatus there are two principal classifications: *First*, according to the function of the machines; Motors, Generators. Boosters, Motor-Generators, Dynamotors, Double-Current Generators, Converters and Phase Advancers; *Second*, according to the type of construction or principle of operation; Commutating, Synchronous, Induction, Unipolar, Rectifying. Obviously, some of these machines could be rationally included in either classification, *e.g.*, Motor-Generators and Rectifying Machines.

In the following, self-evident definitions have for the most part, been omitted.

ROTATING MACHINES.

FUNCTIONAL CLASSIFICATION OF ROTATING MACHINES.

101 **Generator.** A machine which transforms mechanical power into electrical power.

102 **Motor.** A machine which transforms electrical power into mechanical power.

103 **Booster.** A generator inserted in series in a circuit to change its voltage. It may be driven by an electric motor (in which case it is termed a motor-booster) or otherwise.

104 **Motor-Generator Set.** A transforming device consisting of a motor mechanically coupled to one or more generators.

105 **Dynamotor.** A transforming device combining both motor and generator action in one magnetic field, either with two armatures, or with one armature having two separate windings and independent commutators.

106 **A Direct-Current Compensator** or **Balancer** comprises two or more similar direct-current machines (usually with shunt or compound excitation) directly coupled to each other and connected in series across the outer conductors of a multiple-wire system of distribution, for the purpose of maintaining the potentials of the intermediate wires of the system, which are connected to the junction points between the machines.

107 **A Double-Current Generator** supplies both direct and alternating currents from the same armature-winding.

108 **A Converter** is a machine employing mechanical rotation in changing electrical energy from one form into another. There are several types of converters as follow:

109 **A Direct-Current Converter** converts from a direct current to a direct current, usually with a change of voltage. Such a machine may be either a motor-generator set or a dynamotor.

110 **A Synchronous Converter** (sometimes called a Rotary Converter) converts from an alternating to a direct current, or vice-versa. It is a synchronous machine with a single closed-coil armature winding, a commutator and slip rings.

111 **A Cascade Converter,** also called a **Motor Converter,** is a combination of an induction motor with a synchronous converter, the secondary circuit of the former feeding directly into the armature of the latter; *i.e.*, it is a synchronous converter concatenated with an induction motor.

112 **A Frequency Converter** converts the power of an alternating-current system from one frequency to another, with or without a change in the number of phases, or in the voltage.

113 **A Rotary Phase-Converter** converts from an alternating-current system of one or more phases to an alternating-current system of a different number of phases, but of the same frequency.

114 A **Phase Advancer** is a machine which supplies reactive volt-amperes to the system to which it is connected. Phase advancers may be either synchronous or asynchronous.

115 **A Synchronous Condenser** or **Synchronous Phase Advancer** is a synchronous machine, running either idle or with load, the field excitation of which may be varied so as to modify the power-factor of the system, or through such modification to influence the load voltage.

CONSTRUCTIONAL CLASSIFICATION OF ROTATING MACHINES

Commutating Machines

130 **Direct-Current Commutating Machines** comprise a magnetic field of constant polarity, an armature, and a commutator connected therewith. These include: Direct-Current Generators; Direct-Current Motors; Direct-Current Boosters; Direct-Current Motor-Generator Sets and Dynamotors; Direct-Current Compensators or Balancers; and Arc Machines.

131 **Alternating-Current Commutating Machines*** comprise a magnetic field of alternating polarity, an armature, and commutator connected therewith.

132 **Synchronous Commutating Machines** include synchronous converters, cascade-converters, and double-current generators.

133 **Synchronous Machines** comprise a constant magnetic field and an armature receiving or delivering alternating-currents in

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*A suggested classification of alternating-current commutator motors is given in the July 1916 Proceedings of the Institute synchronism with the motion of the machine; *i.e.*, having a frequency strictly proportional to the speed of the machine. They may be sub-divided as follow:

134 **An Alternator** is a synchronous alternating-current generator, either single-phase or polyphase.

135 **A Polyphase Alternator** is a polyphase synchronous alternating-current generator, as distinguished from **a single-phase alternator.**

136 **An Inductor Alternator** is an **Alternator** in which both field and armature windings are stationary, and in which masses of iron or inductors by moving past the coils, alter the magnetic flux through them. It may be either single-phase or polyphase.

137 **A Synchronous Motor** is a machine structurally identical with an alternator, but operated as a motor.

138 **Induction Machines** include apparatus wherein primary and secondary windings rotate with respect to each other; *i.e.*, induction motors, induction generators, certain types of frequency converters and certain types of rotary phase-converters.

139 **An Induction Motor** is an alternating-current motor, either singlephase or polyphase, comprising independent primary and secondary windings, one of which, usually the secondary, is on the rotating member. The secondary winding receives power from the primary by electromagnetic induction.

140 **An Induction Generator** is a machine structurally identical with an induction motor, but driven above synchronous speed as an alternating-current generator.

141 **Unipolar or Acyclic Machines** are direct-current machines, in which the voltage generated in the active conductors maintains the same direction with respect to those conductors.

SPEED CLASSIFICATION OF MOTORS.

150 **Motors** may, for convenience, be classified with reference to their speed characteristics as follow:

151 **Constant-Speed Motors,** whose speed is either constant or does not materially vary; such as synchronous motors, induction motors with small slip, and ordinary direct-current shunt motors.

152 **Multispeed Motors** (two-speed, three-speed, etc.), which can be operated at any one of several distinct speeds, these speeds being practically independent of the load; such as motors with two armature windings, or induction motors in which the number of poles is changed by external means.

153 **Adjustable-Speed Motors,** in which the speed can be varied gradually over a considerable range, but when once adjusted remains practically unaffected by the load; such as shunt motors designed for a considerable range of speed variation.

154 **Varying-Speed Motors,** or motors in which the speed varies with the load, ordinarily decreasing when the load increases; such as series motors, compound-wound motors, and series-shunt motors. As a sub-class of varying-speed motors, may be cited, **adjustable varying-speed motors,** or motors in which the speed can be varied over a considerable range at any given load, but when once adjusted, varies with the load; such as compound-wound motors arranged for adjustment of speed by varying the strength of the shunt field.

CLASSIFICATION OF ROTATING MACHINES RELATIVE TO THE DEGREE OF ENCLOSURE OR PROTECTION

160 The following types are recognized:

- Open
- Protected
- Semi-enclosed
- Enclosed
- Separately ventilated
- Water-cooled
- Self-ventilated
- Drip-proof
- Moisture-resisting
- Submersible
- Explosion-proof
- Explosion-proof slip-ring enclosure

161 An **"open" machine** is of either the pedestal-bearing or end-bracket type where there is no restriction to ventilation, other than that necessitated by good mechanical construction.

162 A **"protected" machine** is one in which the armature, field coils, and other live parts are protected mechanically from accidental or careless contact, while free ventilation is not materially obstructed.

163 A **"semi-enclosed" machine** is one in which the ventilating openings in the frame are protected with wire screen, expanded metal, or other suitable perforated covers, having apertures not exceeding ½ of a square inch (3.2 sq. cm.) in area.

164 An **" enclosed " machine** is so completely enclosed by integral or auxiliary covers as to prevent a circulation of air between the inside and outside of its case, but not sufficiently to be termed air-tight.

165 A **" separately ventilated " machine** has its ventilating air supplied by an independent fan or blower external to the machine.

166 A **" water-cooled " machine** is one which mainly depends on water circulation for the removal of its heat.

167 A **" self-ventilated " machine** differs from a separately ventilated machine only in having its ventilating air circulated by a fan, blower, or centrifugal device integral with the machine.

If the heated air expelled from the machine is conveyed away through a pipe attached to the machine, this should be so stated.

168 A **"drip-proof"** **machine** is one so protected as to exclude falling moisture or dirt. A "drip proof" machine may be either "open" or "semi-enclosed", if it is provided with suitable protection integral with the machine, or so enclosed as to exclude effectively falling solid or liquid material.

169 A **moisture-resisting machine** is one in which all parts are treated with moisture-resisting material. Such a machine shall be capable of operating continuously or intermittently in a very humid atmosphere, such as in mines, evaporating rooms, etc.

170 A **"submersible" machine** is a machine capable of withstanding complete submersion, in fresh water or sea water, as may be specified, for four hours without injury.

171 **An "explosion-proof" machine** is a machine in which the enclosing case can withstand, without injury, any explosion of gas that may occur within it, and will not transmit the flame to any inflammable gas outside it.

172 An induction motor in which the slip rings and brushes alone are included within an explosion-proof case should not be described as an explosion-proof machine, but as a machine "**with explosion-proof slip-ring enclosure.**"

STATIONARY INDUCTION APPARATUS

200 **Stationary Induction Apparatus** changes electric energy to electric energy, through the medium of magnetic energy, without mechanical motion. It comprises several forms, distinguished as follow:

201 **Transformers**, in which the primary and secondary windings are ordinarily insulated one from another.

202 The terms **"high-voltage"** and **"low-voltage"** are used to distinguish the winding having the greater from that having the lesser number of turns. The terms **"primary"** and **"secondary"** serve to distinguish the windings in regard to energy flow, the primary being that which receives the energy from the supply circuit, and the secondary that which receives the energy by induction from the primary.

203 The **rated current of a constant-potential transformer** is that secondary current which, multiplied by the rated-load secondary voltage, gives the kv-a. rated output. That is, a transformer of given kv-a. rating must be capable of delivering the rated output at rated secondary voltage, while the primary impressed voltage is increased to whatever value is necessary to give rated secondary voltage.

The **Rated Primary Voltage** of a constant-potential transformer is the rated secondary voltage multiplied by the turn ratio.

204 The **ratio of a transformer,** unless otherwise specified, shall be the ratio of the number of turns in the high-voltage winding to that in the low-voltage winding; *i.e.*, the **"turn-ratio"**

205 The **voltage ratio** of a transformer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary terminal voltage, under specified conditions of load.

206 The "**current ratio**" of a current-transformer is the ratio of r.m.s. primary current to r.m.s. secondary current, under specified conditions of load.

207 The "**marked ratio**" of an instrument transformer is the ratio which the apparatus is designed to give under average conditions of use. When a precise ratio is required, it is necessary to specify the voltage, frequency, load and power factor of the load.

208 **Volt-Ampere Ratio of Transformers.**

The volt-ampere ratio, which should not be confused with real efficiency, is the ratio of the volt-ampere output to the volt-ampere input of a transformer, at any given power factor.

209 **Auto-transformers** have a part of their turns common to both primary and secondary circuits.

210 **Voltage Regulators** have turns in shunt and turns in series with the circuit, so arranged that the voltage ratio of the transformation or the phase relation between the circuit-voltages is variable at will They are of the following three classes:

211 **Contact Voltage Regulators,** in which the number of turns in one or both of the coils is adjustable.

212 **Induction Voltage Regulators,** in which the relative positions of the primary and secondary coils are adjustable.

213 **Magneto Voltage Regulators,** in which the direction of the magnetic flux with respect to the coils is adjustable.

214 **Reactors,** heretofore commonly called **Reactance Coils,** also called **Choke Coils**; a form of stationary induction apparatus used to supply reactance or to produce phase displacement. **See also §82 and 736.**

METERS AND INSTRUMENTS

225 Although the terms **Instruments** and **Meters** are frequently used synonymously in referring to electrical measuring devices, the meter departments of manufacturing and operating companies commonly use the word "meters" in the collective sense to designate only those devices which register the total energy or quantity of electricity consumed in or supplied to a circuit, and reserve the term "instruments," in the collective sense, for all other electrical measuring or indicating devices.

226 In general, the names of meters and instruments are self-defining, particularly when considered in connection with existing definitions. The following terms are preferred to other terms sometimes used for the same devices: **Reactive-Factor Meter, Power-Factor Meter, Watt-hour Meter,** etc.

227 **Crest Voltmeter.** A voltmeter depending for its indications upon the crest, that is the maximum value of the voltage of the system to which it is connected. These instruments are so calibrated that they indicate the r. m. s. value of the sinusoidal voltage having the same crest value.

228 **Synchronoscope** (also called a Synchroscope or Synchronism Indicator). A device which in addition to indicating synchronism between two machines, shows whether the speed of the incoming machine is fast or slow.

229 **Reactive-Volt-Ammeter** (also called a Reactive-Volt-Ampere Indicator). An instrument which indicates the reactive volt-amperes of the circuit to which it is connected.

230 **Line Drop Voltmeter Compensator.** A device used in connection with a voltmeter which causes it to indicate the voltage at some distant point of the circuit.

231 **Recording Ammeters, Voltmeters, Wattmeters, etc.,** are instruments which record graphically upon time-charts the values of the quantities they measure.

232 **A Demand Meter** is a device which indicates or records the demand or maximum demand (See §§**57** and **58**). In practice two types are recognized:

233 **An Integrated-Demand Meter** is one which indicates or records the maximum demand obtained through integration.

234 **A Lagged-Demand Meter** is one in which the indication of maximum demand is subject to a characteristic time lag.

235 **Errors of Indicating Instruments.** In specifying the accuracy of an indicating instrument, the error at any point on the scale shall be expressed as a percentage of the full scale reading.

236 **Torque** of meters and instruments shall be expressed in millimeter-grams.

STANDARDS FOR ELECTRICAL MACHINERY

250 *The expressions " machinery " and " machines " are here employed in a general sense, in order to obviate the constant repetition of the words " machinery or induction apparatus."*

251 *All temperatures are to be understood as centigrade.*

252 *The expression " capacity " is to be understood as indicating " capability ", except where specifically qualified, as, for instance, in the case of allusions to electrostatic capacity, i. e., capacitance.*

253 *Wherever special rules are given for any particular type of machinery or apparatus (such as switches, railway motors, railway substation machinery, etc., these special rules shall be followed, notwithstanding any apparent conflict with the provisions of the more general sections. In the absence of special rules on any particular point, the general rules on this point shall be followed.*

260 **Objects of Standardization.** To ensure satisfactory results, electrical machinery should be specified to conform to the Institute Standardization Rules, in order that it shall comply, in operation, with approved limitations in the following respects, so far as they are applicable.

Operating temperature
Mechanical strength
Commutation
Dielectric strength
Insulation resistance
Efficiency
Power factor
Wave shape
Regulation

261 **Capacity or Available Output of an Electrical Machine.** So far as relates to the purposes of these Standardization Rules, the Institute defines the Capacity of an Electrical Machine as the load which it is capable of carrying for a specified time (or continuously), without exceeding in any respect the limitations herein set forth.

Except where otherwise specified, the capacity of an electrical machine shall be expressed in terms of its available *output*. For exceptions see **§277** and **802.**

262 **Rating of an Electrical Machine.** Capacity should be distinguished from Rating. The Rating of a machine is the output marked on the Rating Plate, and shall be based on, but shall not exceed, the maximum* load which can be taken from the machine under prescribed conditions of test. This is also called the rated output.

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*The term "maximum Load" does not refer to loads applied solely for mechanical commutation, or similar tests.

263 **The Principle upon which Machine Ratings** are based, so far as relates to thermal characteristics, is that the rated load, applied continuously or for a stated period, shall produce a temperature rise which, superimposed upon a standard ambient temperature, will not exceed the maximum safe operating temperature of the insulation.

264 **A. I. E. E. and I. E. C. Ratings.** When the prescribed conditions of test are those of the A. I. E. E. Standardization Rules, the rating of the machine is the Institute Rating. (See **§620**). When the prescribed conditions of the test are those of the I. E. C.† Rules, the rating of the machine is the I. E. C. rating. A machine so rated in either case may bear a distinctive sign upon its rating plate.

265 **Standard Temperature and Barometric Pressure for Institute Rating.** The Institute Rating (See **§262**) of a machine shall be its capacity when operating with a cooling medium of the ambient temperature of reference (40° for air or 25° for water, see **§305** and **309**) and with barometric conditions within the range given in §308. See §§**305A, 307, 320** and **321.**

266 **The Temperature Rises Specified in these Rules** apply to all ambient temperatures up to and including, but not exceeding, 40°C. for air and 25°C. for water. (For definition of ambient temperature see **§303**.)

267 **Any Machinery Destined for Use with Higher Ambient** temperatures of cooling mediums, and also any machinery for operation at altitudes for which no provision is made in **§308**, should be the subject of special guarantee by the manufacturer. The methods of test and performance set forth in these Rules will, however, afford guidance in such cases.

UNITS IN WHICH RATING SHALL BE EXPRESSED

274 The rating of **Direct-Current Generators,** shall be expressed in kilowatts (kw.) available at the terminals at a specified voltage.

275 The rating of **Alternators** and **Transformers,** shall be expressed in kilovolt-amperes (kv-a.) available at the output terminals, at a specified voltage and power factor.

276 It is strongly recommended that the **rating of motors** shall be expressed in kilowatts* (kw.) available at the shaft. (An ex-

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†I.E.C. stands for "International Electrotechnical Commission. This rating has not yet been established.

*Since the input of machinery of this class is measured in electrical units and since the output has a definite relation to the input, it is logical and desirable to measure the delivered power in the same units as are employed for the received power. Therefore, the output of motors should be expressed in kilowatts instead of in horse power. However, on account of the hitherto prevailing practice of expressing mechanical output in horse power, it is recommended that for machinery of this class the rating should, for the present, be expressed both in kilowatts and in horse power; as follows:

kw.————approx. equiv. h.p.————

For the purposes of these Rules the horse-power shall be taken as 746.0 watts. In order to lay stress upon the preferred future basis, it is desirable that on Rating plates, the Rating in kilowatts shall be shown in larger and more prominent characters than the rating in horse power.

ception to this rule is made in the case of Railway motors, which, for some purposes, are also rated by their ***input***, see **§802.**)

277 **Auxiliary machinery,** such as regulators, resistors, reactors, balancer sets, stationary and synchronous condensers, etc., shall have their ratings appropriately expressed. It is essential to specify also the voltage (and frequency, if a-c.,), of the circuits on which the machinery may appropriately be used.

KINDS OF RATING

There are various kinds of rating such as:

281 **Continuous Rating.** A machine rated for continuous service shall be able to operate continuously at its rated output, without exceeding any of the limitations referred to in **§260.**

282 **Short-Time Rating.** A machine rated for short-time service; (*i.e.* service including runs alternating with stops of sufficient duration to ensure substantial cooling), shall be able to operate at its rated output during a limited period, to be specified in each case, without exceeding any of the limitations referred to in **§260.** Such a rating is a **short-time rating.**

283 **Nominal Ratings.** For railway motors and sometimes for railway substation machinery, certain nominal ratings are employed. See **§§765** and **800.** Nominal ratings for automobile propulsion motors and generators are not recommended; see **§837.**

284 **Duty-Cycle Operation.** Many machines are operated on a cycle of duty which repeats itself with more or less regularity. For purposes of rating, either a continuous or a short-time equivalent load, may be selected, which shall simulate as nearly as possible the thermal conditions of the actual duty cycle.

285 **Standard durations of equivalent tests** shall be for machines operating under specified duty-cycles **as follow** (see also **§836**):

5 minutes
10 "
15 "
30 "
60 "
120 "
and continuous.

Of these the first six are short-time ratings, selected as being thermally equivalent to the specified duty cycle.

When, for example, a short-time rating of 10 minutes duration is adopted, and the thermally equivalent load is 25 kw. for that period, then such a machine shall be stated to have a 10-minute rating of 25 kw.

286 In every case the equivalent short-time test shall commence only when the windings and other parts of the machine are **within 5°C of the ambient temperature** at the time of starting the test.

287 In the absence of any specification as to the kind of rating, the continuous rating shall be understood.*

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*An exception is made in the case of motors for railway service, where in the absence of any specification as to the kind of rating, the **"nominal rating"** as defined in **§319** and **415** shall be understood.

288 Machines marked in accordance with **§264** shall be understood to have a continuous rating, unless otherwise marked in accordance with **§285**.

HEATING AND TEMPERATURE

300 **Temperature Limitations of the Capacity of Electrical Machinery.** The capacity, so far as relates to temperature, is usually limited by the maximum temperature at which the materials in the machine, especially those employed for insulation, may be operated for long periods without deterioration. When the safe limits are exceeded, deterioration is rapid. The insulating material becomes permanently damaged by excessive temperature, the damage increasing with the length of time that the excessive temperature is maintained, and with the amount of excess temperature, until finally the insulation breaks down.

301 The result of operating at temperatures in excess of the safe limit is to shorten the life of the insulating material. This shortening of life is, in certain special cases, warranted, when necessary for obtaining some other desirable result, as, for example, in some instances of railway and other motors for propelling vehicles, in providing greater power within a limited space. See **§804**. Further instances may also be noted in the cases of contactors, controllers, induction-starters, arc-lamp-magnet windings, etc., designed and constructed for operation at relatively high temperatures.

302 There does not appear to be any advantage in operating at lower temperatures than the safe limits, so far as the life of the insulation is concerned. Insulation may break down from various causes, and when these breakdowns occur, it is not usually due to the temperature at which the insulation has been operated, provided the safe limits have not been exceeded.

303 **The Ambient Temperature** is the temperature of the air or water which, coming into contact with the heated parts of a machine, carries off its heat. See **§§309, 310** and **314.**

304 **The cooling fluid may** either be led to the machine through ducts, or through pipes, or merely surround the machine freely. In the former case the ambient temperature is to be measured at the intake of the machine itself. In the latter case see **§314.**

305 **Ambient Temperature of Reference for Air.** The standard ambient temperature of reference, when the cooling medium is air, shall be 40°C.

305A. **Whatever may be the Ambient Temperature** when the machine is in service, the limits of the maximum observable temperature or of temperature rise specified in the rules should not be exceeded in service; for, if the maximum temperature be exceeded, the insulation may be endangered, and if the rise be exceeded, the excess load may lead to injury, by exceeding limits other than those of temperature; such as commutation, stalling load and mechanical strength. For similar reasons, loads in excess of the rating should not be taken from a machine.

306 The permissible rises in temperature given in column 2 of table III page 38 have been calculated on the basis of the standard ambient temperature of reference, by subtracting 40° from the highest temperatures permissible, which are given in column 1 of the same table.

307 A machine may be tested at any convenient ambient temperature, preferably not below 15°C., but *whatever be the value of this ambient temperature, the permissible rises of temperature must not exceed those given in column* 2 *of table III page* 38.

308 **Altitude.** Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which a machine is intended to work in ordinary service, this height is assumed not to exceed 1000 meters (3300 feet.) For machinery operating at an altitude of 1000 meters or less, a test at any altitude less than 1000 meters is satisfactory, and no correction shall be applied to the observed temperatures. Machines intended for operation at higher altitudes shall be regarded as special. See **§267.** It is recommended that when a machine is intended for service at altitudes above 1000 meters (3300 ft.) the permissible temperature rise at sea level, until more nearly accurate information is available, shall be reduced by 1 per cent for each 100 meters (330 ft.) by which the altitude exceeds 1000 meters. Water cooled oil transformers are exempt from this reduction.

309 **Ambient Temperature of Reference for Water-Cooled Machinery.** For water-cooled machinery, the standard temperature of reference for incoming cooling water shall be 25° C, measured at the intake of the machine.

310 **In the testing of water-cooled transformers,** it is not necessary to take into account the surrounding-air temperature, except where the cooling effect of the air is 15 per cent or more of the total cooling effect, referred to the standard ambient temperature of reference of 25°C. for water and 40°C. for air. When the effect of the cooling air is 15 per cent. or more of the total, the temperature of the cooling water should be maintained within 5°C. of the surrounding air. Where this is impractical, the ambient temperature should be determined from the change in the resistance of the windings, using a disconnected transformer, supplied with the normal amount of cooling water, until the temperature of the windings has become constant.

311 **In the case of rotating machines,** cooled by forced draught, a conventional weighted mean shall be employed, a weight of four being given to the temperature of the circulating air supplied through ducts (see **§304**), and a weight of one to the surrounding room air. **In the case of air-cooled transformers,** see " exception " **§321.**

312 **Machines Cooled by Other Means.** Machines cooled by means other than air or water shall receive special consideration.

313 **Outdoor Machinery Exposed to Sun's Rays.** Outdoor machinery not protected from the sun's rays at times of heavy load, shall receive special consideration.

314 **Measurement of the Ambient Temperature During Tests of Machinery.** The ambient temperature is to be measured by means of several thermometers placed at different points around and half-way up the machine, at a distance of 1 to 2 meters (3 to 6 feet), and protected from drafts, and abnormal heat radiation, preferably as in **§316**.

315 The value to be adopted for the ambient temperature during a test, is the mean of the readings of the thermometers (placed as above), taken at equal intervals of time during the last quarter of the duration of the test.

316 Inorder to avoid **errors due to the time lag** between the temperature of large machines and the variations in the ambient air, all reasonable precautions must be taken to reduce these variations and the errors arising therefrom. Thus, the thermometer for determining the ambient temperature shall be immersed in a suitable liquid, such as oil, in a suitable heavy metal cup. This can be made to respond to various rates of change, by proportioning the amount of oil to the metal in the containing cup. A convenient form for such an oil-cup consists of a massive metal cylinder, with a hole drilled partly through it. This hole is filled with oil and the thermometer is placed therein with its bulb well immersed. The larger the machine under test, the larger should be the metal cylinder employed as an oil-cup in the determination of the ambient temperature. The smallest size of oil cup employed in any case shall consist of a metal cylinder 25 mm. in diameter and 50 mm. high (1 in. in diameter and 2 in. high).

317 **Thermometers used for taking temperatures of Machinery** shall be covered by felt pads 3 mm. (⅛ inch) thick and 4 x 5 cm. wide (1½"x 2"), cemented on; oil putty may be used for stationary and small apparatus.

318 **In Transformer Testing,** and sometimes in testing other machines, it may be desirable to avoid errors due to time lag in temperature changes, by employing an idle unit of the same size and subjected to the same conditions of cooling as the unit under test, for obtaining the ambient temperature as described in **§310**.

319 Where **machines are partly below the floor line** in pits, the temperature of the rotor shall be referred to a weighted mean of the pit and room temperatures, the weight of each being based on the relative proportions of the rotor in and above the pit. Parts of the stator constantly in the pit shall be referred to the ambient temperature in the pit.

320 **Correction for the Deviation of the Ambient Temperature of the Cooling Medium, at the Time of the Heat Test, from the Standard Ambient Temperature of Reference.** Numerous experiments have shown that deviation of the temperature of the cooling medium from that of the standard of reference, at the time of the heat run, has a negligible effect upon the temperature rise of the apparatus; therefore, no correction shall be applied for this deviation. It is, however, desirable that tests should be conducted at ambient temperatures not lower than 15°C.

321 *Exception*—**A Correction shall be applied** to the observed temperature rise of the windings of *Air-blast transformers,* due to difference in resistance, when the temperature of the ingoing cooling air differs from that of the standard of reference. This correction shall be the ratio of the inferred absolute ambient temperature of reference to the inferred absolute temperature of the ingoing cooling air, *i. e.* the ratio 274.5/(234.5 + *t*); where *t* is the ingoing cooling-air temperature.

Thus, a cooling-air room temperature of 30°C. would correspond to an inferred absolute temperature of 264.5° on the scale of copper resistivity, and the correction to 40°C. (274.5° inferred absolute temperature) would be 274.5 / 264.5 = 1.04, making the correction factor 1.04; so that an observed temperature rise of say 50°C. at the testing ambient temperature of 30°C. would be corrected to 50 × 1.04 = 52°C. this being the temperature rise which would have occurred had the test been made with the standard ingoing cooling-air temperature of 40°C.

322 **Duration of Temperature Test of Machine for Continuous Service** The temperature test shall be continued until sufficient evidence is available to show that the maximum temperature and temperature rise would not exceed the requirements of the rules, if the test were prolonged until a steady final temperature was reached.

323 **Duration of Temperature Test of Machine with a Short-Time Rating.** The duration of the temperature test of a machine with a short-time rating shall be the time required by the rating. (See **§285** and **286**).

324 **Duration of Temperature Test for Machine having more than One Rating.** The duration of the temperature test for a machine with more than one rating shall be the time required by that rating which produces the greatest temperature rise. In cases where this cannot be determined beforehand, the machine shall be tested separately under each rating.

325 **Temperature Measurements during Heat Run.** Temperature measurements, when possible, shall be taken during operation, as well as when the machine is stopped. The highest figures thus obtained shall be adopted. In order to abridge the long heating period, in the case of large machines, reasonable overloads of current, during the preliminary period, are suggested for them.

TEMPERATURE MEASUREMENTS

340 **The Life of the Insulation of a Machine** depends in great measure upon the actual temperatures attained by the different parts, rather than on the rises of temperature in those parts.

341 **The Temperatures in the Different Parts of a Machine** which it would be desirable to ascertain, are the maximum temperatures reached in those parts.

343 **As it is Usually Impossible to Determine the Maximum Temperature** attained in insulated windings, it is convenient to apply a correction to the observable temperature, which approximates the difference between the actual maximum temperature and the observable temperature by the method used. This correction, or margin of security, is provided to cover the errors due to fallibility in the location of the measuring devices, as well as inherent inaccuracies in measurement and methods.

344 **In Determining the Temperature of Different Parts of a Machine** three methods are provided.

345 **Method No 1. Thermometer Method.**

This method consists in the determination of the temperature, by mercury or alcohol thermometers, by resistance thermometers, or by thermocouples, any of these instruments being applied to the hottest accessible part of the *completed* machine, as distinguished from the thermocouples or resistance coils embedded in the machine as described under Method No. 3.

346 **When Method No. 1 is Used,** the hottest-spot temperature for windings shall be estimated by adding a hottest-spot correction of 15°C to the highest temperature observed, in order to allow for the practical impossibility of locating any of the thermometers at the hottest spot.

Vol. 35
1916

347 *Exception*. When the thermometers are applied directly to the surfaces of bare windings, such as an edgewise strip conductor, or a cast copper winding, a hottest-spot correction of 5°C, instead of 15°C, shall be made. For commutators, collector rings, bare metallic surfaces not forming part of a winding, or for oil in which apparatus is immersed, no correction is to be applied.

348 **Method No. 2. Resistance Method.**

This method consists in the measurement of the temperature of windings by their increase in resistance, corrected* to the instant of shut-down when necessary. In the application of this method, *thermometer measurements shall also be made* whenever practicable without disassembling the machine† in order to increase the probability of revealing the highest observable temperature. Whichever measurement yields the higher temperature, that temperature shall be taken as the "highest observable" temperature and a hottest-spot correction of 10°C added thereto.

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*Whenever a sufficient time has elapsed between the instant of shut-down and the time of the final temperature measurement to permit the temperature to fall, suitable corrections shall be applied, so as to obtain as nearly as practicable the temperature at the instant of shut-down. This can sometimes be approximately effected by plotting a curve, with temperature readings as ordinates and times as abscissas, and extrapolating back to the instant of shut-down. In other instances, acceptable correction factors can be applied. In transformers of 200 kv-a. and less the measured temperature shall be increased one degree for every minute between the instant of shut-down and the time of the final temperature measurement, provided this time does not exceed three minutes.

In cases where successive measurements show *increasing* temperatures after shut-down, the highest value shall be taken.

†As one of the few instances in which the thermometer check cannot be applied in Method No. 2, the rotor of a turbo-alternator may be cited.

349 **The Temperature Coefficient of Copper** shall be deduced from the formula $1/(234.5 + t)$. Thus, at an initial temperature $t = 40$°C., the temperature co-efficient of increase in resistance per degree centigrade rise, is $1/(274.5) = 0.00364$. The following table, deduced from the formula, is given for convenience of reference.

TABLE II.

Temperature Coefficients of Copper Resistance.

Temperature of the winding, in degrees C. at which the initial resistance is measured.	Increase in resistance of copper per °C., per ohm of initial resistance.
0	0.00 427
5	0.00 418
10	0.00 409
15	0.00 401
20	0.00 393
25	0.00 385
30	0.00 378
35	0.00 371
40	0.00 364

350 **In Circuits of Low Resistance,** other than transformer windings (see §351), where joints and connections form a considerable part of the total resistance, the measurement of temperature by the resistance method shall not be used.

351 **The Temperature of the Windings of Transformers** is always to be ascertained by Method 2. In the case of air-blast transformers, it is especially important to place thermometers on the coils near the air outlet. See §348.

352 **Method No. 3. Embedded Temperature-Detector Method.**

This method consists in the use of thermo-couples or resistance temperature detectors, located as nearly as possible at the estimated hottest spot. When method No. 3 is used, it shall, when required, be checked by method No. 2; the hottest spot shall then be taken to be the highest value by either method, the required correction factors (§348 and §356) being applied in each case.

353 **By Building into the Machine** suitably placed temperature detectors, a temperature not much less than that of the hottest spot will probably be disclosed. When these devices are adopted for such

temperature determinations, a liberal number shall be employed, and all reasonable efforts, consistent with safety, shall be made to locate them at the various places where the highest temperatures are likely to occur.

354 **Temperature-Detectors** should be placed in at least two sets of locations. One of these should be between a coil-side* and the core and one between the top and bottom coil-sides where two coil-sides per slot are used. Where only one coil-side per slot is used, one set of detectors shall be placed between coil-side and core, and one set between coil-side and wedge.

355 Method No. 3 should be applied to all stators of machines with cores having a width of 50 cm. (20 in.) and over. It should also be applied to all machines of 5000 volts and over, if of over 500 kv-a., regardless of core width. This method is not required for induction-regulators, which shall be tested as transformers.

356 **Correction Factor for Method No. 3.**—In the case of two-layer windings, with detectors between coil-sides, and between coil-side and core, add 5° C to the highest reading. In single-layer windings, with detectors between coil-side and core and between coil-side and wedge, add to the highest reading 10° C. plus 1° C. per 1000 volts above 5000 volts of terminal pressure.

TEMPERATURE LIMITS

375 Table III, page 38, gives the limits for the hottest-spot temperatures of insulations. The permissible limits are indicated in column 1 of the Table. The limits of temperature rise permitted under rated-load conditions are given in column 2, and are found by subtracting 40° C. from the figures in column 1. Whatever be the ambient temperature at the time of the test, the rise of temperature must never exceed the limits in column 2 of the table. The highest temperatures, and temperature rises, attained in any machine at the output for which it is rated, must not exceed the values indicated in the Table and clauses following.

376 **Permissible Temperatures and Temperature Rises For Insulating Materials.** Table III (see next page) gives the highest temperatures and temperature rises to which various classes of insulating materials may be subjected, based on a standard ambient temperature of reference of 40°C.

377 NOTE. The Institute recognizes the ability of manufacturers to employ Class B insulation successfully at maximum temperatures of 150° C. and even higher. However, as sufficient data covering experience over a period of years at such temperatures are at present unavailable, the Institute adopts 125° C as a conservative limit for this class of insulation, and any increase above this figure should be the subject of special guarantee by the manufacturer.

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*A coil side is one of the two active sides of the coil lying in a slot.

TABLE III.

Permissible Temperatures and Temperature Rises for Insulating Materials.

Class	Description of Material	1 Maximum Temperature to which the material may be subjected	2 Maximum Temperature Rise
A.	Cotton, silk, paper and similar materials, when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enamelled wire[*]	105°C	65°C
B.	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A. material or binder is used for structural purposes only, and may be destroyed without impairing[†] the insulating or mechanical qualities of the insulation	125°C	85°C
C.	Fireproof and refractory materials, such as pure mica, porcelain, quartz, etc......	No limits specified.	

[*] For cotton, silk, paper and similar materials, when neither treated, impregnated nor immersed in oil, the highest temperatures and temperature rises shall be 10°C below the limits fixed for Class A, in Table III.

[†] The word impair is here used in the sense of causing any change which would disqualify the insulation for continuous service.

378 When a lower-temperature class material is comprised in a completed product to such an extent, or in such ways, that its subjection to the temperature limits allowed for the higher-temperature class material, with which it is associated, would affect the integrity of the insulation either mechanically or electrically, the permissible temperature shall be fixed at such a value as shall afford ample assurance that no part of the lower-temperature class material shall be subjected to temperatures higher than those approved by the Institute and set forth above.

379

TABLE IV

Permissible Hottest Spot Temperatures and Limiting Observable Temperature Rises in Other than Water-Cooled Machinery

		Class	A*	B
		Permissible Hottest-Spot Temperature....	105°	125°
METHOD I THERMOMETER ONLY See §345 to 347		Hottest Spot Correction..................	15°	15°
		Limiting Observable Temperature.........	90°	110°
		Limiting Observable Temperature Rise	50°	70°
METHOD II RESISTANCE See §348		Hottest Spot Correction..................	10°	10°
		Limiting Observable Temperature.........	95°	115°
		Limiting Observable Temperature Rise	55°	75°
METHOD III EMBEDDED TEMPERATURE DETECTORS See § 352 to §356	Double-Layer Windings. For all Voltages	Hottest Spot Correction.......	5°	5°
		Limiting Observable Temperature..................	100°	120°
		Limiting Observable Temperature Rise..........	60°	80°
	Single-Layer Windings. For 5000 volts or less	Hottest Spot Correction.......	10°	10°
		Limiting Observable Temperature..................	95°	115°
		Limiting Observable Temperature Rise....	55°	75°
	Single-Layer Windings. For more than 5000 Volts	Hottest Spot Correction	$10° + (E-5)$ †	$10° + (E-5)$
		Limiting Observable Temperature..................	$95° - (E-5)$	$115° - (E-5)$
		Limiting Observable Temperature Rise	$55° - (E-5)$	$75° - (E-5)$

*For cotton, silk, paper and similar materials, when neither treated, impregnated nor immersed in oil, the highest temperatures and temperature rises shall be 10°C. below the limits fixed for class A.

†In these formulas, E represents the rated pressure between terminals in kilovolts. Thus for a three-phase machine with single-layer winding, and with 11 kilovolts between terminals, the hottest-spot correction to be added to the maximum observable temperature will be 16°C.

Special Cases of Temperature limits.

385 **Temperature of Oil.** The oil in which apparatus is permanently immersed shall in no part have a temperature, observable by thermometer, in excess of 90°C.

386 **Water-Cooled Transformers.** In these the hottest-spot temperature shall not exceed 90°C.

386A **Enclosed Motors and Generators.** In an enclosed machine (see §**164**) the limiting observable temperature and the limiting observable temperature rise shall be taken as 5°C. higher than in Table IV. This is not to be interpreted as an increase in the permissible hottest spot temperature, but is in recognition of the lesser difference between the hottest spot temperature and the observable temperature within an enclosed machine. This rule does not apply to those types of machines defined in §§**163**, **165** and **167**.

387 **Railway Motor Temperature Limits,** see §**804** and **805**.

387A. **Automobile Propulsion Motors and Generators,** see §**838**.

388 **Squirrel-Cage and Amortisseur Windings.** In many cases the insulation of such windings is largely for the purpose of making the conductors fit tightly in their slots, and the slightest effective insulation is ample. In other cases, there is practically no insulating material on the windings. Consequently, the temperature rise may be of any value such as will not occasion mechanical injury to the machine.

389 **Collector Rings.** The temperature of collector rings shall not be permitted to exceed the " hottest-spot " values set forth in §**376** and **379** for the insulations employed either in the collector rings themselves, or in adjacent insulations whose life would be affected by the heat from the collector rings.

390 **Commutators.** The observable temperature shall in no case be permitted to exceed the values given in §**376** and **379** for the insulation employed, either in the commutator or in any insulation whose life would be affected by the heat of the commutator. These temperature limits are intended only to protect the insulation of the commutator and of the adjacent parts, and are not intended as a criterion of successful commutation. See §**402**.

391 **Cores.** The temperature of those parts of the iron core in contact with insulating materials must not be such as to occasion in those insulating materials temperatures or temperature rises in excess of those set forth in §**376** and **379**.

392 **Other parts,** (such as brush-holders, brushes, bearings, pole-tips, cores, etc.) All parts of electrical machinery other than those whose temperature affects the temperature of the insulating material, may be operated at such temperatures as shall not be injurious in any other respect.

METHODS OF LOADING TRANSFORMERS FOR TEMPERATURE TESTS

393 Whenever practicable, transformers should be tested under conditions that will give losses approximating as nearly as possible to those obtained under normal or specified load conditions, maintained for the required time (See **§322** to **324**). The maximum temperature rises measured during this test should be considered as the observable temperature rises for the given load.

An approved method of making these tests is the "**loading-back**" method. The principal variations of this method are:

394 **With duplicate single-phase transformers.**

Duplicate single-phase transformers may be tested in banks of two, with both primary and secondary windings connected in parallel. Normal magnetizing voltage should then be applied and the required current circulated from an auxiliary source. One transformer can be held under normal voltage and current conditions, while the other may be operating under slightly abnormal conditions.

395 **With one three-phase transformer.**

One three-phase transformer may be tested in a manner similar to **§394** provided the primary and secondary windings are each connected in delta for the test. Normal three-phase magnetizing voltage should be applied and the required current circulated from an auxiliary single-phase source.

396 **With three single-phase transformers.**

Duplicate single-phase transformers may be tested in banks of three, in a manner similar to **§395** by connecting both primary and secondary windings in delta, and applying normal three-phase magnetizing voltage and circulating the required current from an auxiliary single-phase source.

397 Note:— Among other methods that have a limited application and can be used only under special conditions may be mentioned—

(1) Applying dead load by means of some form of rheostat.

(2) Running alternately for certain short intervals of time on open circuit and then on short circuit, alternating in this way until the transformer reaches steady temperature. In this test, the voltage for the open-circuit interval and the current for the short-circuit interval shall be such as to give the same integrated core loss, and the same integrated copper loss, as in normal operation.

ADDITIONAL REQUIREMENTS

398 **Short-Circuit Stresses.**

The Institute recognizes the self-destructibility, both mechanical and thermal, of certain sizes and types of machines, when subjected to severe short-circuits, and recommends that ample protection be provided in such cases, external to the machine if necessary.

Over-Speeds.

399 **All Types of Rotating Machines** shall be so constructed that they will safely withstand an over-speed of 25 per cent, except in the case of steam turbines, which, when equipped with emergency governors, shall be constructed to withstand 20 per cent over-speed.

400 **In the case of Series Motors,** it is impracticable to specify percentage values for the guaranteed over-speed, on account of the varying service conditions.

401 **Water-wheel Generators** shall be constructed for the maximum runaway speed which can be attained by the combined unit.

Momentary Loads.

402 **Continuously Rated Machines** shall be required to carry momentary loads of 150 per cent of the amperes corresponding to the continuous rating, keeping the rheostat set for rated load excitation, (See **§281, 764** and **803**.) and commutating machinery shall commutate successfully under this condition. Successful commutation is such that neither brushes nor commutator are injured by the test. In the case of direct-connected generators, this clause is not to be interpreted as requiring the prime mover to drive the generator at this overload.

403 **Machines for duty-cycle operation** shall be rated according to their equivalent load, either on the short-time or continuous basis, but if intended for operation with widely fluctuating loads, shall commutate successfully under their specified operating conditions. See **§ 284, 285.**

404 **Stalling Torque of Motors**

Motors for continuous service shall, except when otherwise specified, be required to develop a running torque at least 175 per cent of that corresponding to the running torque at their rated load, without stalling.

Obviously, duty-cycle machines must carry their peak loads without stalling.

WAVE FORM

405 The **Sine Wave** shall be considered as standard, except where deviation therefrom is inherent in the operation of the system of which the machine forms a part.

406 **The deviation of wave form** from the sinusoidal is determined by superposing upon the actual wave, (as determined by oscillograph), the equivalent sine wave of equal length, in such a manner as to give the least difference between ordinates, and then dividing the maximum difference between corresponding ordinates by the maximum value of the equivalent sine wave. A maximum deviation of the terminal voltage wave on open circuit from sinusoidal shape not exceeding 10 per cent is permissible, except when otherwise specified.

EFFICIENCY AND LOSSES

420 **Machine Efficiency** is the ratio of the power delivered by the machine to the power received by it.

421 **Plant or System Efficiency** is the ratio of the energy delivered from the plant or system to the energy received by it in a specified period of time.* In calculating plant or system efficiency it may be desirable to calculate the losses in each individual machine or part of the system at the actual temperature of that machine or part during the specified interval. These losses may be appreciably different from the losses at 75°C., which lattershall be the standard temperature of reference for all efficiency guarantees. See **§432**.

422 **In the Case of Machinery two Efficiencies are Recognized,** conventional efficiency (see **§423**) and directly measured efficiency. Unless otherwise specified, the conventional efficiency is to be employed. When the efficiency of a machine is stated without specific reference to the load conditions, rated load is always to be understood whether the efficiency be the conventional or directly measured efficiency.

423 **Conventional Efficiency** of machinery is the ratio of the output to the sum of the output and the losses; or of the input minus the losses to the input; when, in either case, conventional values are assigned to one or more of these losses. The need for assigning conventional values to certain losses, arises from the fact that some of the losses in electrical machinery are practically indeterminable, and must, in many cases, either be approximated by an approved method of test, or else values recommended by the Institute and designated "conventional" values shall be employed for them in arriving at the "conventional efficiency."

425 **Directly-Measured Efficiency.** Input and output determinations of efficiency may be made directly, measuring the output by brake, or equivalent, where applicable. Within the limits of practical application, the circulating-power method, sometimes described as the Hopkinson or "loading-back" method, may be used.

426 **Values of the Indeterminate Losses** may also be obtained by brake or other direct test, and used in estimating actual efficiencies of similar machines, by the separate-loss method.

427 **Normal Conditions.** The efficiency shall correspond to, or be corrected to, the normal conditions herein set forth, which shall be regarded as standard. These conditions include voltage, current, power-factor, frequency, wave-shape, speed, temperature, or such of them as may apply in each particular case.

428 **Measurement of Efficiency.** Electric power shall be measured at the terminals of the apparatus. In polyphase machines, sufficient measurements shall be made on all phases to avoid errorsofunbalance.

429 **Point at Which Mechanical Power Shall be Measured.** Mechanical power delivered by machines, shall be measured at the pulley,

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*An exception should be noted in the case of the efficiency of storage batteries.

gearing, or coupling, on the rotor shaft, thus excluding the loss of power in the belt or gear friction. See, however, an exception in **§800**.

430 **The Efficiency Specified for Alternators and Transformers** shall be of the ratio of the kilowatt output to the kilowatt input at the rated kv-a. and power factor.

431 **Efficiency of Alternating-Current Machinery in regard to WaveShape.** In determining the efficiency of alternating-current machinery, the sine wave is to be considered as standard, unless a different wave form is inherent in the operation of the system. See **§405**.

432 **Temperature of Reference for Machine Efficiency.** The efficiency, at all loads, of all apparatus, shall be corrected to a reference temperature of 75°C, but tests may be made at any convenient ambient temperature, preferably not less than 15°C. See §§**348** and **445**.

433 **The losses in constant-potential machinery,** either of the stationary type, or of the constant-speed rotary type, are of two classes; namely, those which remain substantially constant at all loads, and those which vary with the load. The former include iron losses, windage and friction, also I^2R losses in any shunt windings. The latter include I^2R losses in series windings. The constant losses may be determined by measuring the power required to operate the machine at no load, deducting any series I^2R losses. The variable loss at any load may be computed from the measured resistance of the series windings and the given load current.

434 **Stray Load Losses.** The above simple method of determining the losses and hence the efficiency is only approximate, since the losses which are assumed to be constant do actually vary to some extent with the load, and also because the actual loss in the copper windings is sometimes appreciably greater than the calculated I^2R loss. The difference between the approximate losses, as above determined, and the actual losses, is termed the " stray load losses "*. These latter are due to distortions in electric or magnetic fluxes from their no-load distributions or values, brought about by the load current. They are usually only approximately measurable, or may be indeterminable.

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*In Table V, the stray load losses include f, h, i, k, l and m; but do not include increased core losses due to increased excitation for compensating internal drop under load.

TABLE V

Classification of Losses in Machinery

435 Losses in machinery may be classified as follows:

Accurately Measurable or Determinable	*Approximately Measurable or Determinable*	*Indeterminable*
a. No-Load Core Losses including eddy-current losses in conductors at no-load	*c.* Brush Friction Loss	*h.* Iron Loss due to flux distortion.
b. Load I^2R losses in windings No-Load I^2R losses in windings	*d.* Brush-Contact Loss	*i.* Eddy-Current losses in conductors due to transverse fluxes occasioned by the load currents.
	e. Losses due to windage and to bearing friction	*k.* Eddy-Current losses in conductors due to tooth saturation resulting from distortion of the main flux.
	f. Extra copper loss in transformer windings, due to stray fluxes caused by load currents	*l.* Tooth-frequency losses due to flux distortion under load.
	g. Dielectric Losses.	*m.* Short-Circuit Loss of Commutation.

436 **Evaluation of Losses.** The larger individual losses are either accurately or approximately determinable, but certain of the indeterminable losses reach values in various kinds of machinery which require that they should be taken into account.

LOSSES TO BE TAKEN INTO ACCOUNT IN VARIOUS TYPES OF MACHINES

440 **Direct-Current Commutating Motors and Generators.**

Core losses. See **§452**.

I^2R loss in all windings.

Brush contact I^2R loss. Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush; *i. e.*, 2 volts for total brush drop, either carbon or graphite brushes. (See **§§454** and **819**). In the case of low voltage automobile propulsion motors and generators this loss should be determined experimentally; see **§839**.

Friction of bearings and windage.

Rheostat losses, when present.

Brush friction.

All indeterminable load losses (including stray-load iron losses) which may be important, which vary with the design, and for which no satisfactory method of determination has been found, shall be included as zero per cent in estimating conventional efficiency.

441 **Synchronous Motors and Generators.**

Core losses. See **§452.**

I^2R loss in all windings, based upon rated k-va. and power factor.

Stray load-losses. In approximating these losses, the method described in **§458** shall be employed.

Friction of bearings and windage.

Brush friction and brush-contact loss is negligible, except in the case of revolving armature machines.

Rheostat losses, when present, corresponding to rated kv-a. and power factor.

442 **Induction Machines.**

Core losses. See **§452.**

I^2R losses in all windings.

Stray load-losses. In approximating these losses, the method described in **§459** shall be employed

Brush friction when collector rings are present.

Brush-contact loss. Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See **§454.**

Friction of bearings and windage.

443 **Commutating A-C. Machines**

Core losses. See **§452.**

I^2R losses in all windings.

Brush friction.

Brush-contact loss. Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See **§454** and **819.**

Friction of bearings and windage.

Short-circuit loss of commutation. Iron loss due to flux distortion. Eddy-current losses due to fluxes varying with load and saturation.	The Institute is not at this time prepared to make recommendations for approximating these losses.

144 **Synchronous Converters.**

Core losses. See **§452.**

I^2R losses in all windings, based on rated kw. and unity power factor. The I^2R losses in the armature winding shall be derived from those corresponding to its use as a direct-current generator, by using suitable factors.

Brush friction.

Rheostat losses when present, corresponding to rated kw. and unity power factor.

Brush-contact loss. Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See **§454**.

Short-circuit loss of commutation.	These losses, while usually of low magnitude, are erratic, and the Institute is not at this time prepared to make recommendations for approximating them.
Iron loss due to flux distortion when present.	
Eddy-current losses due to fluxes varying with load and saturation.	

Friction of bearings and windage.

For the booster type of synchronous converter, where the booster forms an integral part of the unit, its losses shall be included in the total converter losses in estimating the efficiency.

445 Transformers

No-load losses. These include the core loss, and the I^2R loss due to the exciting current, also the dielectric loss in the insulation. (See **§470**).

Load losses. These include I^2R losses, and stray load-losses due to eddy currents caused by fluxes varying with load. (See **§471**).

DETERMINATION OR APPROXIMATION OF LOSSES IN ROTATING MACHINERY

450 **Bearing Friction and Windage** may be determined as follows. Drive the machine from an independent motor, the output of which shall be suitably determined. The machine under test shall have its brushes removed and shall not be excited. This output represents the bearing friction and windage of the machine under test.

The bearing friction and windage of induction motors may be measured by running motors free at the lowest voltage at which they will rotate continuously at approximately rated speed; the watts input, minus I^2R loss, under these conditions being taken as the friction and windage.

In the case of engine-type generators, the windage and bearing friction loss is ordinarily very small, amounting to a fraction of one per cent of the output. In these rules this loss is neglected owing to its small value and the difficulty of measuring it.

451 **Brush Friction of Commutator and Collector Rings.** Follow the test of **§450,** taking an additional reading with the brushes in contact with the commutator or collector rings. The difference between the output obtained in the test in **§450** and this output shall be taken as the brush friction. Note: The surfaces of the commutator and brushes should already be smooth and glazed from running when this test is made.

452 **Core Loss.** Follow the test of **§451** with an additional reading taken in a similar manner, except that the machine is to be excited so as to produce at the terminals a voltage corresponding to the calculated internal voltage for the load under consideration. The difference between the output obtained by this test and that obtained by test under Sec. **451** shall be taken as the core loss.

For Synchronous Machines, the internal voltage shall be determined by correcting the terminal voltage for the resistance drop only.

The Core Loss of Induction Motors may be determined by measuring the watts input to the motor when running free at rated voltage and frequency and subtracting therefrom the no-load copper loss, bearing friction and windage.

454 **The Brush-Contact I^2R Loss** depends largely upon the material of which the brush is composed. As indicating the range of variation the following table will be of interest:

TABLE VI.

Brush-Contact Drop.

Grade of Brush	Volts drop across one brush-contact. (Average of positive and negative brushes)
Hard Carbon	1.1
Soft Carbon	0.9
Graphite	0.5 to 0.8
Metal-Graphite types	0.15 to 0.5 (The former for largest proportion of metal)

One volt drop per brush shall be considered as the Institute Standard drop corresponding to the I^2R brush-contact loss, for carbon and graphite brushes. Metal-graphite brushes shall be considered as special. See **§819.**

455 **Field-Rheostat Losses** shall be included in the generator losses where there is a field rheostat in series with the field magnets of the generator, even when the machine is separately excited.

456 **Ventilating Blower.** When a blower is supplied as part of a machine set, the power required to drive it shall be charged against the complete unit; but not against the machine alone.

457 **Losses in Other Auxiliary Apparatus.** Auxiliary apparatus, such as a separate exciter for a generator or motor, shall have its losses charged against the plant of which the generator and exciter are a part, and not against the generator. An exception should be noted in the case of turbo-generator sets with direct-connected exciters, in which case the losses in the exciter shall be charged against the generator. The actual energy of excitation and the field-rheostat losses, if any, (see §455) shall be charged against the generator.

458 **Stray Load-Losses in Synchronous Generators and Motors.** These include iron losses, and eddy-current losses in the copper, due to fluxes varying with load and also to saturation.

Stray load-losses are to be determined by operating the machine on short circuit and at rated-load current. This, after deducting the windage and friction and I^2R loss, gives the stray load-loss for polyphase generators and motors. These losses in single-phase machines are large; but the Institute is not yet prepared to specify a method for measuring them.

459 **Stray Load-Losses in Induction Machines.**

These include eddy-current losses in the stator copper, and other eddy-current losses due to fluxes varying with the load. In windings consisting of relatively small conductors, these eddy-current losses are usually negligible.

With rotor removed, measure the power input to the stator with different values of current at the rated frequency. The curve plotted with these values gives the combined I^2R and stray load-losses due to eddy currents in the stator copper. Deduct the I^2R loss determined from the resistance, and the difference will represent the stray load-losses corresponding to the various currents. While this method is not accurate for some types of motors it usually represents a sufficiently good approximation.

460 **Polyphase Induction-Motor Rotor I^2R Loss.** This should be determined from the slip, whenever the latter is accurately determinable, using the following equation:

$$\text{Rotor } I^2R \text{ loss} = \frac{\text{Output} \times \text{slip}}{1 - \text{slip}}$$

In large slip-ring motors, in which the slip cannot be directly measured by loading, the rotor I^2R loss shall be determined by direct resistance measurement; the rotor full-load current to be calculated by the following equation:

$$\text{Current per ring} = \frac{\text{watts output}}{\text{rotor voltage at stand-still} \times \sqrt{3} \times K}$$

This equation applies to three-phase rotors. For rotors wound for two phase, use 2 instead of the $\sqrt{3}$. K may be taken as 0.95 for motors of 150 kw. or larger. The factor K usually decreases as the size of motor is reduced, but no specific value can be stated for smaller sizes.

DETERMINATION OR APPROXIMATION OF LOSSES IN TRANSFORMERS

470 **No-Load Losses.** These shall be measured with open secondary circuit at the rated frequency, and with an applied primary voltage

giving the rated secondary voltage plus the IR drop which occurs in the secondary under rated load conditions.

471 **Load Losses.** These include I^2R and stray load-losses. They shall be measured by applying a primary voltage, preferably at rated frequency, sufficient to produce rated load current in the windings, with the secondary windings short circuited.

DIELECTRIC STRENGTH TESTS OF MACHINERY

480 **Basis for Determining Test Voltages.** The test voltage which shall be applied to determine the suitability of insulation for commercial operation is dependent upon the kind and size of the machinery, and its normal operating voltage, upon the nature of the service in which it is to be used, and upon the severity of the mechanical and electrical stresses to which it may be subjected. The voltages and other conditions of test which are recommended, have been determined as reasonable and proper for the great majority of cases, and are proposed for general adoption, except when specific reasons make a modification desirable.

481 **Condition of Machinery to be Tested.** Commercial tests shall, in general, be made with the completely assembled machinery and not with individual parts. The machinery shall be in good condition, and high-voltage tests, unless otherwise specified, shall be applied before the machine is put into commercial service, and shall not be applied when the insulation resistance is low owing to dirt or moisture. High-voltage tests shall be made at the temperature assumed under normal operation or at the temperature attained under the conditions of commercial testing. High-voltage tests to determine whether specifications are fulfilled, are admissible on new machines only. Unless otherwise agreed upon, high-voltage tests of a machine shall be understood as being made at the factory.

482 **Points of Application of Voltage.** The test voltage shall be successively applied between each electric circuit and all other electric circuits and metal parts grounded.

483 **Interconnected Polyphase Windings** are considered as one circuit. All windings of a machine except that under test, shall be connected to ground.

484 **Frequency, Wave Form and Test Voltage.** The frequency of the testing circuit shall not be less than the rated frequency of the apparatus tested. A sine-wave form is recommended. See **§405**. The test shall be made with alternating voltage having a crest value equal to $\sqrt{2}$ times the specified test voltage. In d.c. machines, and in the general commercial application of a.c. machines, the testing frequency of 60 cycles per second is recommended.

485 **Duration of Application of Test Voltage.** The testing voltage for all classes of apparatus shall be applied continuously for a period of 60 seconds. See exception, **485A**.

485A *Exception*—**For All Standard Devices Produced in Large Quantities** and with a standard test pressure of 2500 volts or less, a test pressure applied for one second 20 per cent higher than the one-minute test pressure will be satisfactory.

486 **Apparatus for Use on Single-Phase, 3-Phase-Delta or 3-Phase-Star Circuits.** Apparatus, such as transformers, which may be used in star connection on three-phase circuits, shall have the delta voltage of the circuits on which they may be used indicated on the rating plate and the test shall be based on such delta voltage.

VALUES OF A-C. TEST VOLTAGES

500 **The Standard Test for All Classes of Apparatus, Except as Otherwise Specified, Shall be Twice the Normal Voltage of the Circuit to Which the Apparatus is Connected, Plus 1000 Volts.**

501 *Exception*—**Alternating-Current Apparatus connected to Permanently Grounded Single-Phase Systems, for use on Permanently Grounded Circuits of more than 300 Volts,** shall be tested with 2.73 times the voltage of the circuit to ground + 1000 volts. This does not refer to three-phase apparatus with grounded star neutral.

502 *Exception*—**Distributing Transformers.** Transformers for primary pressures from 550 to 5000 volts, the secondaries of which are directly connected to consumers' circuits and commonly known as distributing transformers, shall be tested with 10,000 volts from primary to core and secondary combined. The secondary windings shall be tested with twice their normal voltage plus 1000 volts.

503 *Exception*—**Auto-Transformers** used for starting purposes, shall be tested with the same voltage as the test voltage of the apparatus to which they are connected

504 *Exception*—**Household Devices.** Apparatus taking not over 660 watts† and intended solely for operation on supply circuits not exceeding 250 volts, shall be tested with 900 volts, except in the case of heating devices which shall be tested with 500 volts at operating temperature.

505 *Exception*—**Apparatus for use on Circuits of 25 Volts or Lower,** such as bell-ringing apparatus,* electrical apparatus used in automobiles, apparatus used on low-voltage battery circuits, etc., shall be tested with 500 volts.

506 *Exception*—**Field Windings of Alternating-Current Generators** shall be tested with 10 times the exciter voltage, but in no case with less than 1500 volts nor more than 3500 volts.

507 *Exception*—Field Windings‡ of Synchronous Machines, including motors and converters which are to be started from alternating-current circuits, shall be tested as follows:

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†The present National Electric Code power limit for a single outlet.

*This rule does not include bell-ringing transformers of ratio 125 to 6 volts. See National Electric Code.

‡Series field coils should be regarded as part of the armature circuit and tested as such.

a. When machines are started with fields short-circuited they shall be tested as specified in §506.

b. When machines are started with fields open-circuited and sectionalized while starting, they shall be tested with 5000 volts.

c. When machines are started with fields open-circuited and connected all in series while starting, they shall be tested with 5000 volts for less than 275-volt excitation and 8000 volts for excitation of 275 volts to 750 volts.

508 *Exception*. **Phase-Wound Rotors of Induction Motors.** The secondary windings of wound rotors of induction motors shall be tested with twice their normal induced voltage, plus 1000 volts. By normal induced voltage is here meant the voltage between slip rings on open circuit at standstill with normal voltage impressed on the primary.

When induction motors with phase-wound rotors are reversed, while running at approximately normal speed, by reversing the primary connections, the test shall be four times the normal induced voltage, plus 1000 volts.

509 *Exception*—**Switches and Circuit Control Apparatus above 600 volts,** shall be tested with 2½ times rated voltage, plus 2000 volts. See §720 to 741.

510 *Exception*—**Assembled Apparatus.** Where a number of pieces of apparatus are assembled together and tested as an electrical unit, they shall be tested with 15 per cent lower voltage than the lowest required on any of the individual pieces of apparatus.

510A *Exception.* **Meters and Instruments.** The Institute is not at present in a position to make a recommendation in regard to the dielectric tests of meters and instruments.

511 **Testing Transformers by Induced Voltage.** Under certain conditions it is permissible to test transformers by inducing the required voltage in their windings, in place of using a separate testing transformer. By "required voltage", is meant a voltage such that the line end of the windings shall receive a test to ground equal to that required by the general rules.

512 **Transformers with Graded Insulation** shall be so marked. They shall be tested by inducing the required test-voltage in the transformer and connecting the successive line leads to ground.

Transformer windings permanently grounded within the transformer shall be tested by inducing the required test voltage in such windings. (See §500).

MEASUREMENT OF VOLTAGE IN DIELECTRIC TESTS OF MACHINERY

530 **Use of Voltmeters and Spark-Gaps in Insulation Tests.** When making insulation tests on electrical machinery. every

precaution must be taken against the occurrence of any spark-gap discharges in the circuits from which the machinery is being tested. A non-inductive resistance of about one ohm per volt shall be inserted in series with one terminal of the spark gap. If the test is made with one electrode grounded, this resistance shall be inserted directly in series with the non-grounded electrode. If neither terminal is grounded, one-half shall be inserted directly in series with each electrode. In any case this resistance shall be as near the measuring gap as possible and not in series with the tested apparatus. The resistance will damp high-frequency oscillations at the time of breakdown and limit the current which will flow. A water tube is the most reliable form of resistor. Carbon resistors should not be used because their resistance may become very low at high voltages.

531 **For Machinery of Low Capacitance.** When the machinery under test does not require sufficient charging current to distort the high-voltage wave shape, or change the ratio of transformation, the spark gap should be set for the required test voltage and the testing apparatus adjusted to give a voltage at which this spark gap just breaks down. This adjustment should be made with the apparatus under test disconnected. The apparatus should then be connected, and with the spark gap about 20 per cent longer, the testing apparatus is again adjusted to give the voltage of the former breakdown, which is the assumed voltage of test. This voltage is to be maintained for the required interval.

532 **For Machinery of High Capacitance.** When the charging current of the machinery under test may appreciably distort the voltage wave or change the effective ratio of the testing transformer, the first adjustment of voltage with the gap set for the test voltage should be made with the apparatus under test connected to the circuit and in parallel with the spark gap.

When making arc-over tests of large insulators, leads, etc. partial arc-over of the tested apparatus may produce oscillations which will cause the measuring gap to discharge prematurely. The measured voltage will then appear too high. In such tests the " equivalent " ratio " of the testing transformer should be measured by gap to within 20% of the arc-over voltage of the tested apparatus with the tested apparatus in circuit. The measuring gap should then be greatly lengthened out and the voltage increased until the tested apparatus arcs over. This arc-over voltage should then be determined by multiplying the voltmeter reading by the equivalent ratio found above. Direct measurement of the spark-over voltage over one gap by another gap should always be avoided.

533 **Measurements with Voltmeter.** In measuring the voltage with a voltmeter, the instrument should preferably derive its voltage from the high-tension circuit, either directly, or by means of a voltmeter coil placed in the testing transformer, or through an auxiliary *ratio transformer*. It is permissible to measure the voltage at other places, such as the transformer primary provided cor-

rections can be made for the variations in ratio caused by the charging current of the machinery under test, or provided there is no material variation of this ratio. In any case, when the capacitance of the apparatus to be tested is such as to cause wave distortion, the testing voltage must be checked by a spark gap as set forth in **§538**, or by a crest voltage meter. If the crest-voltage meter is calibrated in crest volts, its readings must be reduced to the corresponding r. m. s. sinusoidal value by dividing with $\sqrt{2}$.

534 **Measurements with Spark Gaps**. If proper precautions are observed, spark gaps may be used to advantage in checking the calibration of voltmeters when set up for the purposes of high-voltage tests of the insulation of machinery.

535 **Ranges of Voltages.** For the calibrating purposes set forth in **§534** the sphere-gap shall be used for voltages above 50 kv., and is to be preferred down to 30 kv. The needle spark-gap may, however, be used for voltages from 10 to 50 kv.

536 **The Needle Spark Gap.** The needle spark gap shall consist of new sewing needles, supported axially at the ends of linear conductors which are at least twice the length of the gap. There must be a clear space around the gap for a radius of at least twice the gap length.

537 The sparking distances in air between No. 00 sewing needle points for various root-mean-square sinusoidal voltages are as follows:

TABLE VII.

Needle-Gap Spark-Over Voltages

(At 25°C and 760 mm. barometer).

R.M.S. Kilovolts	Millimeters	R.M.S. Kilovolts	Millimeters
10	11.9	35	51
15	18.4	40	62
20	25.4	45	75
25	33	50	90
30	41		

The above values refer to a relative humidity of 80 per cent. Variations from this humidity may involve appreciable variations in the sparking distance.

538 **The Sphere Spark-Gap.** The standard sphere spark-gap shall consist of two suitably mounted metal spheres. When used as specified below, the accuracy obtainable should be approximately 2 per cent.

No extraneous body, or external part of the circuit, shall be nearer the gap than twice the diameter of the spheres. By the "gap" is meant the shortest path between the two spheres.

The shanks should not be greater in diameter than 1/5th the sphere diameter. Metal collars, etc., through which the shanks extend, should be as small as practicable and should not, during any measurement, come closer to the sphere than the maximum gap length used in that measurement.

The sphere diameter should not vary more than 0.1 per cent and the curvature, measured by a spherometer, should not vary more than 1 per cent from that of a true sphere of the required diameter.

539 **In using the spherometer** to measure the curvature, the distance between the points of contact of the spherometer feet should be within the following limits:

TABLE VIII

Spherometer Specifications

Diameter of Sphere in m.m.	Distance between contact points in mm. Maximum	Distance between contact points in mm. Minimum
62.5	35	25
125	45	35
250	65	45
500	100	65

539A **In using Sphere Gaps** constructed as above, it is assumed that the apparatus will be set up for use in a space comparatively free from external dielectric fields. Care should be taken that conducting bodies forming part of the circuit, or at circuit potential, are not so located with reference to the gap that their dielectric fields are superposed on the gap; *e.g.*, the protecting resistance should not be arranged so as to present large masses or surfaces near the gap, even at a distance of two sphere diameters.

In case the sphere is grounded, the spark point of the grounded sphere should be approximately five diameters above the floor or ground.

540 **The sparking distances between different spheres** for various r.m.s sinusoidal voltages shall be assumed to be as follows:

TABLE IX.

Sphere-Gap Spark-Over Voltages

(At 25°C and 760 mm. barometric pressure)

Kilo-volts	Sparking Distance in Millimeters.							
	62.5 mm. spheres		125 mm. spheres		250 mm. spheres		500 mm. spheres	
	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated
10	4.2	4.2	..	..	..	..	..	..
20	8.6	8.6	..	..	..	..	..	..
30	14.1	14.1	14.1	14.1	..	..	..	..
40	19.2	19.2	19.1	19.1	..	..	..	..
50	25.5	25.0	24.4	24.4	..	..	..	..
60	34.5	32.0	30.	30.	29	29	..	..
70	46.0	39.5	36	36	35	35	..	..
80	62.0	49.0	42	42	41	41	41	41
90		60.5	49	49	46	45	46	45
100			56	55	52	51	52	51
120			79.7	71	64	63	63	62
140			108	88	78	77	74	73
160			150	110	92	90	85	83
180				138	109	106	97	95
200					128	123	108	106
220					150	141	120	117
240					177	160	133	130
260					210	180	148	144
280					250	203	163	158
300						231	177	171
320						265	194	187
340							214	204
360							234	221
380							255	239
400							276	257

The sphere gap is more sensitive than the needle gap to momentary rises of voltage and the voltage required to spark over the gap should be obtained by slowly closing the gap under constant voltage, or by slowly raising the voltage with a fixed setting of the gap. Open arcs should not be permitted in proximity to the gap during its operation, as they may affect its calibration.

AIR-DENSITY CORRECTION-FACTORS FOR SPHERE GAPS

541 **The Spark-Over Voltage,** for a given gap, decreases with decreasing barometric pressure and increasing temperature. This correction may be considerable at high altitudes.

The spacing at which it is necessary to set a gap to spark over at some required voltage, is found as follows: Divide the required voltage by the correction factor given below in Table X. A new voltage is thus obtained. The spacing on the standard curves obtained from Table IX, corresponding to this new voltage, is the required spacing.

The voltage at which a given gap sparks over is found by taking the voltage corresponding to the spacing from the standard curves of Table IX, and multiplying by the correction factor.

When the variation from sea level is not great, the relative air density may be used as the correction factor; when the variation is great, or greater accuracy is desired, the correction factor corresponding to the relative air density should be taken from Table X below, in which

$$\text{Relative air density} = \frac{0.392\, b}{273 + t}$$

b = barometric pressure in mm.
t = temperature in deg. C.

Corrected curves may be plotted for any given altitude, if desired.

Values of relative air density and corresponding values of the correction factor are tabulated below. It will be seen that for values above .9, the correction factor does not differ greatly from the relative air density.

TABLE X.

Air-Density Correction Factors for Sphere Gaps

Relative air density	Diameter of standard spheres in mm.			
	62.5	125	250	500
0.50	0.547	0.535	0.527	0.519
0.55	0.594	0.583	0.575	0.567
0.60	0.640	0.630	0.623	0.615
0.65	0.686	0.677	0.670	0.663
0.70	0.732	0.724	0.718	0.711
0.75	0.777	0.771	0.766	0.759
0.80	0.821	0.816	0.812	0.807
0.85	0.866	0.862	0.859	0.855
0.90	0.910	0.908	0.906	0.904
0.95	0.956	0.955	0.954	0.952
1.00	1.000	1.000	1.000	1.000
1.05	1.044	1.045	1.046	1.048
1.10	1.090	1.092	1.094	1.096

INSULATION RESISTANCE OF MACHINERY

550 **The insulation resistance of a machine** at its operating temperature shall be not less than that given by the following formula:

$$\text{Insulation Resistance in megohms} = \frac{\text{voltage at terminals}}{\text{rated capacity in kv-a.} + 1000}$$

The formula only applies to dry apparatus. Such high values are not attainable in oil-immersed apparatus.

Insulation resistance tests shall, if possible, be made at a d.c. pressure of 500 volts. Since the insulation resistance varies with the pressure, it is necessary that, if a pressure other than 500 volts is to be employed in any case, this other pressure shall be clearly specified.

The order of magnitude of the values obtained by this rule is shown in the following table:

TABLE XI.

Insulation Resistance of Machinery

Rated Voltage of machine	Megohms		
	100 kv-a.	1000 kv-a.	10,000 kv-a.
100	0.091	0.05	—
1,000	0.91	0.50	0.091
10,000	9.1	5.0	0.91
100,000	—	50	9.1

551 It should be noted that the insulation resistance of machinery is of doubtful significance by comparison with the dielectric strength. The insulation resistance is subject to wide variation with temperature humidity and cleanliness of the parts. When the insulation resistance falls below that corresponding to the above rule, it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying out the machine. The insulation-resistance test may therefore afford a useful indication as to whether the machine is in suitable condition for the application of the dielectric test.

REGULATION

DEFINITIONS

560 **Regulation.** The regulation of a machine in regard to some characteristic quantity (such as terminal voltage or speed) is the change in that quantity occurring between any two loads. Unless otherwise specified, the two loads considered shall be zero load and rated load, and at the temperature attained under normal operation. The regulation may be expressed by stating the numerical values of the quantity at the two loads, or it may be ex-

pressed by the "percentage regulation", which is the percentage ratio of the change in the quantity occurring between the two loads, to the value of the quantity at either one or the other load, taken as the normal value. It is assumed that all parts of the machine affecting the regulation maintain constant temperature between the two loads, and where the influence of temperature is of consequence, a reference temperature of 75°C shall be considered as standard. If change of temperature should occur during the tests, the results shall be corrected to the reference temperature of 75°C.

The normal value may be either the no-load value, as the no-load speed of induction motors; or it may be the rated-load value, as in the voltage of a.c. generators.

It is usual to state the regulation of d-c. generators by giving the numerical values of the voltage at no load and rated load, and in some cases it is advisable to state regulation at intermediate loads.

561 The **Regulation of d-c. Generators** refers to changes in voltage corresponding to gradual changes in load and does not relate to the comparatively large momentary fluctuations in voltage that frequently accompany instantaneous changes in load.

In determining the regulation of a compound-wound d-c. generator, two tests shall be made, one bringing the load down and the other bringing the load up, between no-load and rated load. These may differ somewhat, owing to residual magnetism. The mean of the two results shall be used.

562 In **constant-potential a-c. generators,** the regulation is the rise in voltage (when the specified load at specified power factor is reduced to zero) expressed in per cent of normal rated-load voltage.

563 In **constant-current machines,** the regulation is the ratio of the maximum difference of current from the rated-load value (occurring in the range from rated-load to short-circuit, or minimum limit of operation), to the rated-load current.

564 In **constant-speed direct-current motors,** and induction motors, the regulation is the ratio of the difference between full-load and no-load speeds to the no-load speed.

565 In **constant-potential transformers,** the regulation is the difference between the no-load and rated-load values of the secondary terminal voltage at the specified power factor (with constant primary impressed terminal voltage) expressed in per cent of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the apparatus delivers rated output at rated secondary voltage.

566 In **converters, dynamotors, motor-generators and frequency converters,** the regulation is the change in the terminal voltage of the output side between the two specified loads. This may be expressed by giving the numerical values, or as the percentage of the terminal voltage at rated load.

567 In **transmission lines, feeders etc.**, the regulation is the change in the voltage at the receiving and between rated non-inductive load and no load, with constant impressed voltage upon the sending

end. The percentage regulation is the percentage change in voltage to the normal rated voltage at the receiving end.

568 In **steam engines, steam turbines and internal combustion engines,** the percentage speed regulation is usually expressed as the percentage ratio of the maximum variation of speed, to the rated-load speed in passing slowly from rated load to no load (with constant conditions at the supply.)

569 If the test is made by passing suddenly from rated load to no load, the immediate percentage speed regulation so derived shall be termed the **fluctuation.**

570 In a **hydraulic turbine,** or other water motor, the percentage speed regulation is expressed as the percentage ratio of the maximum variation in speed in passing slowly from rated load to no load (at constant head of water), to the rated-load speed.

571 In a **generator unit,** consisting of a generator combined with a prime mover, the speed or voltage regulation should be determined at constant conditions of the prime mover; *i.e.* constant steam-pressure, head, etc. It includes the inherent speed variations of the prime mover. For this reason, the regulation of a generator unit is to be distinguished from the regulation of either the prime mover, or of the generator combined with it, when taken separately.

CONDITIONS FOR TESTS OF REGULATION

580 **Speed and Frequency.** The regulation of generators is to be determined at constant speed, and of alternating-current apparatus at constant frequency.

581 **Power Factor.** In apparatus generating, transforming or transmitting alternating currents, the power factor of the load to which the regulation refers should be specified. Unless otherwise specified, it shall be understood as referring to non-inductive load, that is to a load in which the current is in phase with the *e.m f.* at the output side of the apparatus.

582 **Wave Form.** In the regulation of alternating-current machinery receiving electric power, a sine wave of voltage is assumed, except where expressly specified otherwise. See **§405.**

583 **Excitation.** In commutating machines, rectifying machines, and synchronous machines, such as direct-current generators and motors, as well as in alternating-current generators, the regulation is to be determined under such conditions as to maintain the field adjustment constant at that which gives rated-load voltage at rated-load current, as follows:

(1) In the case of separately-excited field magnets—constant excitation.

(2) In the case of shunt machines, constant resistance in the shunt-field circuit.

(3) In the case of series or compound machines, constant resistance shunting the series-field windings.

584 **Tests and Computation of Regulation of A-C. Generators.**

Any one of the three following methods may be used. They are given in the order of preference.

Method a.

The regulation can be measured directly, by loading the generator at the specified load and power factor, then reducing the load to zero, and measuring the terminal voltage, with speed and excitation adjusted to the same values as before the change. This method is not generally applicable for shop tests, particularly on large generators, and it becomes necessary to determine the regulation from such other tests as can be readily made.

585 **Method b.**

This consists in computing the regulation from experimental data of the open-circuit saturation curve and the zero-power-factor saturation curve. The latter curve, or one approximating very closely to it, can be obtained by running the generator with over excitation on a load of idle-running under-excited synchronous motors. The power factor under these conditions is very low and the load saturation curve approximates very closely the zero power factor saturation curve. From this curve and the open circuit curve, points for the load saturation curve, for any power factor, can be obtained by means of vector diagrams.

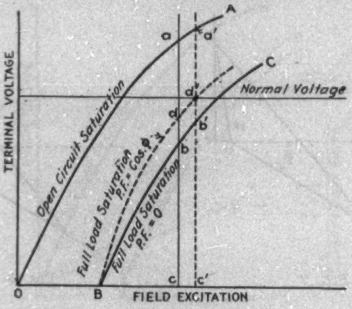


FIG. 1

To apply Method b, it is necessary to obtain from test, the open-circuit saturation curve *OA*, Fig. 1, and the saturation curve *BC* at zero power factor and rated-load current. At any given excitation *Oc*, the voltage that would be induced on open circuit is *ac*, the terminal voltage at zero power factor is *bc*, and the apparent internal drop is *ab*. The terminal voltage *dc* at any other power factor can then be found by drawing an e.m.f. diagram* as in Fig. 2, where ϕ is an angle such that *cos* ϕ is the power factor of the load, *be* the resistance drop (IR) in the stator winding, *ba* the total internal drop, and *ac* the total induced voltage; *ba* and *ac* being laid off to correspond with the values obtained from Fig. 1. The terminal voltage at power factor *cos* ϕ, is then *cb* of Fig. 2, which, laid off in Fig. 1, gives point *d*. By finding a number of such points, the curve *Bdd′* for power factor *cos* ϕ is obtained and the regulation at this power factor (expressed in per cent) is $\frac{100 \times a'd'}{d'c'}$, since $a'd'$ is the rise in voltage when the load at power factor *cos* ϕ is thrown off at normal voltage $c'd'$.

---

*Method b, for deducing the load saturation curve, at any assigned power factor, from no-load and zero power-factor saturation curves obtained by test must be regarded as empirical. Its value depends upon the fact that experience has demonstrated the reasonable correctness of the results obtained by it.

Generally, the ohmic drop can be neglected, as it has very little influence on the regulation, except in very low-speed machines where the armature resistance is relatively high, or in some cases where regulation at unity power factor is being estimated. For low power factors, its effect is negligible in practically all cases. If resistance is neglected, the simpler e.m.f. diagram, Fig. 3, may be used to obtain points on the load saturation curve for the power factor under consideration.

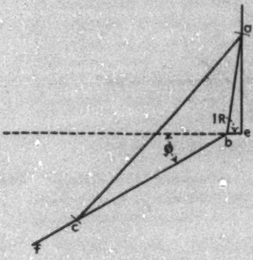


FIG. 2

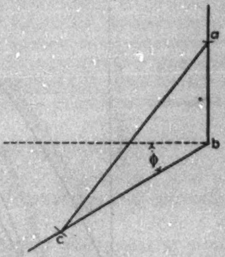


FIG. 3

586 **Method c.**

Where it is not possible to obtain by test a zero-power-factor saturation curve as in Method b, this curve can be estimated closely from open-circuit and short-circuit curves, by reference to tests at zero power factor on other machines of similar magnetic circuit. Having obtained the estimated zero-power-factor curve, the load saturation for any other power factor is obtained as in method b.

Thus Method c is the same as Method b; except that the zero-power-factor curve must be estimated. This may be done as follows. In Fig. 4, *OA* is the open-circuit saturation curve and *OE* the short-circuit line as shown by test. The zero-power-factor curve corresponding to any given current *BF* will start from point *B*, and for machines designed with low saturation and low reactance, will follow parallel to *OA*, as shown by the dotted curve *BD*, which is *OA* shifted horizontally parallel to itself by the distance *OB*. In high-speed machines, or in others having low reactance and a low degree of saturation in the magnetic circuit, the zero-power-factor curve will lie quite close to *BD*, particularly in those parts that are used for determining the regulation. This is the case with many turbo-generators and high-speed water-wheel generators. In many cases, however, the zero-power-factor curve will deviate from *BD*, as shown by *BC*, and the deviation will be most pronounced in machines of high reactance, high saturation, and large magnetic leakage. The position of the actual curve *BC* with relation to *BD*, can be approximated with sufficient exactness by investigating the corresponding relation as obtained by test at zero power factor on machines of similar characteristics and magnetic circuit. Or curve *BC* can be calculated by methods based on the results of tests at zero power factor. After *BC* has been obtained, the saturation curve and regulation for any other power factor can be derived as in Method (b).

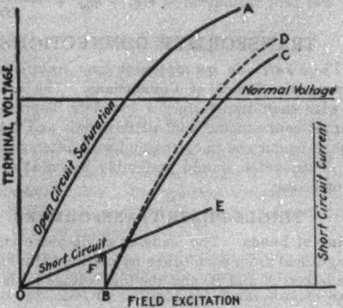


Fig. 4

587 Tests and Computation of Regulation for Constant-Potential Transformers.

The regulation can be determined by loading the transformer and measuring the change in voltage with change in load, at the specified power factor. This method is not generally applicable for shop tests, particularly on large transformers.

The regulation for any specified load and power factor can be computed from the measured impedance watts and impedance volts, as follows:

Let:

P = impedance watts, as measured in the short-circuit test and corrected to 75°C.
E_z = impedance volts, as measured in the short-circuit test.
IX = Reactance Drop in Volts.
I = Rated Primary Current.
E = Rated Primary Voltage.

q_r = percent drop in phase with current.
q_x = percent drop in quadrature with current.

$$IX = \sqrt{E_s^2 - \left(\frac{P}{I}\right)^2}$$

$$q_r = 100\frac{P}{EI}$$

$$q_x = 100\frac{IX}{E}$$

588 Then—

1. For **unity power factor**, we have approximately:-

$$\text{Per cent regulation} = q_r + \frac{q^2_x}{200}$$

589 2. For **inductive loads** of power-factor m and reactive-factor n,

$$\text{Per cent regulation} = mq_r + nq_x + \frac{(mq_x - nq_r)^2}{200}$$

TRANSFORMER CONNECTIONS*

(*These rules do not apply to auto transformers.*)

600 **Diagrammatic Sketch of Connections.** The manufacturer shall furnish with each transformer a complete diagrammatic sketch of the internal connections, and all terminals and taps of the transformer shall be marked to correspond with letters and numbers in the sketch. This sketch should preferably be on a metal plate on the transformer case.

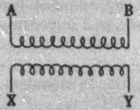
SINGLE-PHASE TRANSFORMERS

601 **Marking of Leads.** The leads of single-phase transformers shall be distinguished from each other by marking the high-voltage leads with the letters A and B, and the low-voltage leads with the letters X and Y.

The terminals (by terminals is meant the ends of the windings) shall be so marked that the potential difference in all windings at any instant shall have the same sign, that is, the potential difference between A and B shall have the same sign at any instant as the potential difference between X and Y.**

602 In accordance with the above rule, the terminals of single-phase transformers shall be marked as follows:

(1) High- and Low-Voltage Windings in Phase:



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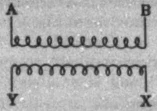
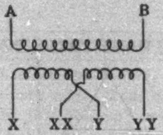
*Sections 601 to 611, relative to a specific scheme of marking the leads, are tentative only, subject to the adoption of a comprehensive scheme of marking the terminals of all classes of apparatus.

**To test the correctness of single-phase markings, connect A to X and apply voltage to the high voltage winding A-B. Voltage B-Y must be numerically less than voltage A-B.

603 (2) High- and Low-Voltage Windings 180 deg. Apart in Phase:

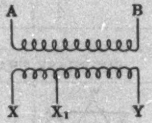


604 **Single-Phase Transformers with More than Two Windings.** Transformers with three or more windings (each being provided with separate outgoing leads) shall have the leads of two of their windings lettered in accordance with the preceding paragraph. The remaining leads shall be designated AA BB, etc. in the case of high-voltage leads and XX, YY, etc. in the case of low-voltage leads. For example, transformers having four secondary leads from two distinct, similar windings shall be lettered as follows:



This indicates that the low-voltage winding consists of two disconnected parts, one part having terminals X, Y and the other part having terminals XX, YY. For multiple connection, X and XX are to be connected and Y and YY are to be connected. For series operation, Y is to be connected to XX.

605 **Tap Connections.** All tap connections which are not brought outside the transformer case shall be marked serially with numerals only. Where tap leads are brought out of the transformer case they shall be given the letter designation together with a subscript indicating the relative position of the tap, as in the following diagram.



606 **Neutral Lead.** Where a neutral lead is brought outside the transformer case, it shall be lettered N.

607 **Parallel Operation.** Transformers marked as above may be operated in parallel, by connecting similarly marked terminals provided their ratios, voltages resistances and reactances are such as to permit parallel operation.

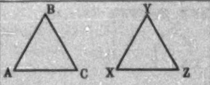
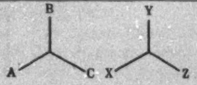
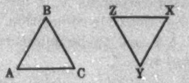
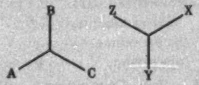
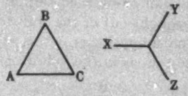
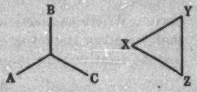
THREE-PHASE TRANSFORMERS

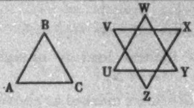
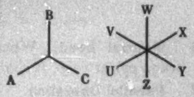
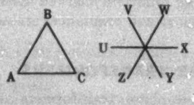
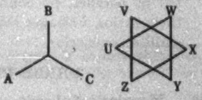
608 **Marking of Leads.** Three-phase transformers ordinarily have three or four leads for high-voltage and three or four leads for low-

voltage windings. To distinguish the various leads from each other, and also to distinguish between the various phase relations obtainable, the three high-voltage leads should be lettered A, B and C and the three low-voltage leads X, Y and Z.

For transformers having six-phase secondaries the primary leads should be lettered A, B and C as above, and the secondary leads U, V, W, X, Y and Z.

The letters shall be so applied to the transformer terminals that if the phase sequence of voltage on the high-voltage side is in the order of A to B to C, it is in the order of X to Y to Z, etc., on the low-voltage side. This arrangement is represented by the diagrams below, which show the various common angular displacements between high- and low-voltage windings of standard transformers. In addition it should be distinctly stated, preferably on the rating plate, in which of the groups given in the following diagrams the transformer belongs.

	THREE-PHASE TRANSFORMERS	
GROUP-1 Angular Displacement 0°		
GROUP-2 Angular Displacement 180°		
GROUP-3 Angular Displacement 30°		

	SIX-PHASE TRANSFORMERS	
GROUP-4 Angular Displacement 0°		
GROUP-5 Angular Displacement 30°		

609 The rules given above for single-phase transformers in regard to the neutral tap (see **§606**), and also in regard to internal connections (see **§§601** to **605**), are applicable to three-phase transformers and six-phase transformers.

610 **Angular Displacement.** The angular displacement between high- and low-voltage windings, is the angle in the diagram in **§608** between the lines passing from the neutral point through *A* and *X* respectively for three-phase transformers and through *A* and *U* for six-phase transformers. Thus, in Group 1, the angular displacement is zero degrees; in Group 2, the angular displacement is 180° and in Group 3, the angular displacement is 30°.

611 **Parallel Operation.** Three-phase and six-phase transformers marked as above may be operated in parallel, by connecting similarly marked terminals together, provided their ratios, voltages, resistances, reactances and angular displacements are such as to permit parallel operation.

INFORMATION ON THE RATING PLATE OF A MACHINE

620 It is recommended that the rating plate of machines which comply with the Institute rules shall carry a distinctive special sign, such as " A.I.E.E. 1916 Rating" or "A16" Rating.

621 The absence of any statement to the contrary on the rating plate of a machine implies that it is intended for continuous service and for the standard altitude and ambient temperature of reference. See **§§287, 305, 308** and **309.**

622 The rating plate of a machine intended to work under various kinds of rating must carry the necessary information in regard to those kinds of ratings.

STANDARDS FOR WIRES AND CABLES

TERMINOLOGY*

635 **Wire.**—A slender rod or filament of drawn metal.

The definition restricts the term to what would ordinarily be understood by the term "solid wire." In the definition, the word "slender" is used in the sense that the length is great in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire; while primarily the term "wire" refers to the metal, nevertheless when the context shows that the wire is insulated, the term "wire" will be understood to include the insulation.

636 **Conductor.**—A wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

The term "conductor" is not to include a combination of conductors insulated from one another, which would be suitable for carrying several different electric currents.

Rolled conductors (such as busbars) are, of course, conductors, but are not considered under the terminology here given.

637 **Stranded Conductor.**—A conductor composed of a group of wires, or of any combination of groups of wires.

The wires in a stranded conductor are usually twisted or braided together.

638 **Cable.**—(1) A stranded conductor (single-conductor cable); or (2) a combination of conductors insulated from one another (multiple-conductor cable).

The component conductors of the second kind of cable may be either solid or stranded, and this kind of cable may or may not have a common insulating covering. The first kind of cable is a single conductor, while the second kind is a group of several conductors. The term "cable" is applied by some manufacturers to a solid wire heavily insulated and lead-covered; this usage arises from the manner of the insulation, but such a conductor is not included under this definition of "cable." The term "cable" is a general one, and, in practise, it is usually applied only to the larger sizes. A small cable is called a "stranded wire" or a "cord," both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead, or with steel wires or bands.

639 **Strand.**—One of the wires, or groups of wires, of any stranded conductor.

640 **Stranded Wire.**—A group of small wires, used as a single wire.

A wire has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands, and is used as a single wire, it is called a "stranded wire." There is no sharp dividing line of size between a "stranded wire" and a "cable." If used as a wire, for example in winding inductance coils or magnets, it is called a stranded wire and not a cable. If it is substantially insulated, it is called a "cord," defined below.

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*From Circular No. 37 of the Bureau of Standards.

641 **Cord.**—A small cable, very flexible and substantially insulated to withstand wear.

There is no sharp dividing line in respect to size between a "cord" and a "cable," and likewise no sharp dividing line in respect to the character of insulation between a "cord" and a "stranded wire." Rubber is used as the insulating material for many classes of cords.

642 **Concentric Strand.**—A strand composed of a central core surrounded by one or more layers of helically-laid wires or groups of wires.

643 **Concentric-Lay Cable.**—A single-conductor cable composed of a central core surrounded by one or more layers of helically-laid wires.

644 **Rope-Lay Cable.**—A single-conductor cable composed of a central core surrounded by one or more layers of helically-laid groups of wires.

This kind of cable differs from the preceding in that the main strands are themselves stranded.

645 **N-Conductor Cable.**—A combination of N conductors insulated from one another.

It is not intended that the name as here given be actually used. One would instead speak of a "3-conductor cable," a "12-conductor cable" etc. In referring to the general case, one may speak of a "multiple-conductor cable" (as in definition §638 above.)

646 **N-Conductor Concentric Cable.**—A cable composed of an insulated central conducting core with (N — 1) tubular stranded conductors laid over it concentrically and separated by layers of insulation.

This kind of cable usually has only two or three conductors. Such cables are used in carrying alternating currents. The remark on the expression "N-conductor" given for the preceding definition applies here also.

647 **Duplex Cable.**—Two insulated single-conductor cables, twisted together.

They may or may not have a common insulating covering.

648 **Twin Cable.**—Two insulated single-conductor cables laid parallel, having a common covering.

649 **Triplex Cable.**—Three insulated single-conductor cables twisted together.

They may or may not have a common insulating covering.

650 **Twisted Pair.**—Two small insulated conductors, twisted together, without a common covering.

The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

651 **Twin Wire.**—Two small insulated conductors laid parallel, having a common covering.

SPECIFICATION OF SIZES OF CONDUCTORS

652 The sizes of solid wires shall be stated by their diameter in mils, the American Wire Gage (Brown and Sharpe) sizes being taken as standard. The sizes of stranded conductors shall be stated by their cross-sectional area in circular mils. For brevity, in cases where the most

careful specification is not required, the sizes of solid wires may be stated by the gage number in the American Wire Gage, and the sizes of stranded conductors smaller than 250,000 circular mils (*i.e.*, No. 0000 A.W.G. or smaller) may likewise be stated by means of the gage number in the American Wire Gage of a solid wire having the same cross-sectional area. Futhermore, an exception is made in the case of "Flexible Stranded Conductors," for which see **§655** below. In **stating large cross-sections,** it is sometimes convenient to use a circular inch (507 sq. mm.) instead of 1,000,000 circular mils.

STRANDING

653 Cables not requiring special flexibility shall be stranded in accordance with the following table.

TABLE XII

Standard Stranding of Concentric Lay-Cables

SIZE (See note 1.)	Number of Wires (See note 2)	
	A Bare, insulated or weatherproof cables for aerial use.	B Insulated cables for other than aerial use.
2.0 Cir. Inches	91	127
1.5 "	61	91
1.0 "	61	61
0.6 "	37	61
0.5 "	37	37
0.4 "	19	37
0000 A. W. G.	19 or 7 (See note 3.)	19
00 "	7	19
2 "	7	7
7 and smaller	..	7

1. For intermediate sizes, use stranding for next larger size.
2. Conductors of 0000 A. W. G. and smaller are often made solid and this table of stranding should not be interpreted as excluding this practice.
3. Class A cable, sizes 0000 and 000 A. W. G., is usually made of 7 strands when bare and 19 strands when insulated or weatherproof.

654 Sectional Area of Cables. The cross-sectional area of a cable shall be considered to be the sum of the cross-sectional areas of its component wires, when measured perpendicular to their axes.

655 **Flexible Stranding.** Conductors of special flexibility should ordinarily be made with wires of regular A.W.G. sizes,* the number of wires and size being given. The approximate gage number or approximate circular mils of such flexible stranded conductors may be stated. The stranding of standard flexible cables is given in Table XIII and a tentative stranding for apparatus cable in Table XIII-A.

TABLE XIII

Proposed Standard Stranding of Flexible Cables

Nearest A.W.G. size (see Note 1)	Circular mils (see Note 3)	Diam. of cable. Mils	No. of wires	Size of each wire A.W.G.	Diam. Mils	Make-up (see Note 2)
	2039000	1836.	703	15.5	53.9	37 × 19
..	1816000	1778.	"	16.0	50.8	"
..	1617000	1680.	"	16.5	48.0	"
..	1440000	1586.	"	17.0	45.3	"
..	1282000	1495.	"	17.5	42.7	"
..	1103000	1372.	427	16.0	50.8	61 × 7
..	874500	1223.	"	17.0	45.3	"
..	693400	1088.	"	18.0	40.3	"
..	550000	969.	"	19.0	35.9	"
..	436400	864.	"	20.0	32.0	"
..	345900	770.	"	21.0	28.5	"
..	274300	686.	"	22.0	25.4	"
..	264700	672.	259	20.0	32.0	37 × 7
0000	209800	599.	"	21.0	28.5	"
000	171300	539.	133	19.0	35.9	19 × 7
00	135900	480.	"	20.0	32.0	"
0	107700	428.	"	21.0	28.5	"
1	82780	332.	91	20.5	30.2	Concentric
2	65660	296.	"	21.5	26.9	"
3	58460	279.	"	22.0	25.4	"
4	39190	229.	61	22.0	25.4	"
5	31080	203.	"	23.0	22.6	"
6	24650	181.	"	24.0	20.1	"
8	17400	152.	"	25.5	16.9	"
10	10560	118.	37	25.5	16.9	"
12	6442	94.	"	27.5	13.4	"
14	4177	74.	"	29.5	10.6	"
Smaller	....	....	To equal Required Size	30.0	....	Bunched

NOTE 1. The A.W.G. sizes except for 61 strands are approximated within 2 per cent. In the case of 61 strand cables the approximation is 6 per cent.

NOTE 2. "61 × 7" signifies a rope-lay cable composed of 61 strands of 7 wires each.

NOTE 3. Circular mils are based on theoretical diameters of A.W.G. sizes which vary above or below values given in table by less than 0.1 mil.

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*Where necessary to closely approximate a regular size cable, the strands may be made of half-size wires from No. 15 to No. 30 A. W. G.

TABLE XIII-A

Proposed Standard Stranding of Apparatus Cables

(This table is offered for consideration but will not be recommended for final adoption until ratified by other societies interested.)

Nearest A.W.G. size (see Note 1)	Circular mils (see Note 3)	Diameter of cable Mils	No. of wires	Size of each wire A.W.G	Diam. Mils	Make-up
..	2053000	1903.	2257	20.5	30.2	61 × 37
..	1829000	1796.	"	21.0	28.5	"
..	1629000	1695.	"	21.5	26.9	"
..	1450000	1600.	"	22.0	25.4	"
..	1291000	1506.	"	22.5	23.9	"
..	1150000	1424.	"	23.0	22.6	"
..	1054000	1359.	1159	20.5	30.2	61 × 19
..	938900	1283.	"	21.0	28.5	"
..	836200	1211.	"	21.5	26.9	"
..	744500	1143.	"	22.0	25.4	"
..	663000	1076.	"	22.5	23.9	"
..	590500	1017.	"	23.0	22.6	"
..	525800	958.	"	23.5	21.3	"
..	451600	889.	703	22.0	25.4	37 × 19
..	402200	836.	"	22.5	23.9	"
..	358200	791.	"	23.0	22.6	"
..	319000	745.	"	23.5	21.3	"
..	284000	703.	"	24.0	20.1	"
..	253000	665.	"	24.5	19.0	"
0000	217600	610.	427	23.0	22.6	61 × 7
000	172500	543.	"	24.0	20.1	"
00	136800	483.	"	25.0	17.9	"
0	104600	422.	259	24.0	20.1	37 × 7
1	82980	376.	"	25.0	17.9	"
2	65810	334.	"	26.0	15.9	"
3	52190	298.	"	27.0	14.2	"
4	42610	268.	133	25.0	17.9	19 × 7
5	33800	238.	"	26.0	15.9	"
6	26800	213.	"	27.0	14.2	"
see Note 2.						

NOTE 1. The A.W.G. sizes are approximated within 3 per cent.

NOTE 2. For sizes smaller than No. 6 see table XIII.

NOTE 3. Circular mils are based on theoretical diameters of A.W.G. sizes, which vary above or below values given in table by less than 0.1 mil.

656 **Correction for Lay.** The resistance and mass of a stranded conductor are greater than in a solid conductor of the same cross-sectional area, depending on the lay (*i.e.*, the pitch of the twist of the wires). Two per cent shall be taken as the standard increment of resistance and of mass. In cases where the lay is definitely known, the increment should be calculated and not assumed.

The direction of lay is the lateral direction in which the strands of a cable run over the top of the cable as they recede from an observer looking along the axis of the cable.

657 The lay of any layer of wires of a cable or strand shall not exceed 15 times the pitch diameter of that layer. The lay of any layer of strands of rope-lay cables shall not exceed 12 times the pitch diameter of the layer.

CONDUCTIVITY OF COPPER.

675 The following I. E. C. rules are adopted:*

The following shall be taken as normal values for standard annealed copper:

(1) At a temperature of 20°C., the resistance of a wire of standard annealed copper one meter in length and of a uniform section of 1 square millimeter is 1/58 ohm = 0.017241....ohm.

(2) At a temperature of 20°C., the density of standard annealed copper is 8.89 grams per cubic centimeter.

(3) At a temperature of 20°C, the "constant mass" temperature coefficient of resistance of standard annealed copper, measured between two potential points rigidly fixed to the wire, is 0.00393 = 1/254.45....per degree centigrade.

(4) As a consequence, it follows from (1) and (2) that, at a temperature of 20 °C. the resistance of a wire of standard annealed copper of uniform section, one meter in length and weighing one gram, is (1/58) × 8.89 = 0.15328......ohm.†§

676 **Copper Wire Tables.** The copper-wire Tables published by the Bureau of Standards in Circular No. 31 are adopted. These Tables are based upon the I. E. C. rules stated in **§675.**

Vol. 35
1916

HEATING AND TEMPERATURE OF CABLES.

677 **Maximum Safe Limiting Temperatures.**

The maximum safe limiting temperature in degrees C. at the surface of the conductor in a cable shall be:—

For impregnated paper insulation	(85—E)
" varnished cambric	(75—E)
" rubber insulation	(60—0.25E)

where E represents the r.m.s. operating e.m.f. in kilovolts between conductors.

Thus, at a working pressure of 3.3 kv., the maximum safe limiting temperature at the surface of the conductor, or conductors, in a cable would be:—

For impregnated paper	81.7°C.
" varnished cambric	71.7°C.
" rubber insulation	59.2°C.

ELECTRICAL TESTS.

678 **Lengths Tested.** Electrical tests of insulation on wires and cables shall be made on the entire lengths to be shipped.

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*See I. E. C. Publication No. 28 "International Standard of Resistance for Copper" March 1914.

†Paragraphs (1) and (4) of § 675 define what are sometimes called "volume resistivity," and "Mass resistivity" respectively. This may be expressed in other units as follows:—volume resistivity = 1.7241 microhms-cm. (or microhms in a cm. cube) at 20°C. = 0.67879 microhm-inch at 20°C., and mass resistivity = 875.20 ohms (mile, pound) at 20°C.

§For detailed specifications of commercial copper, see the "Standard Specifications" of the American Society for Testing Materials.

679 **Immersion in Water.** Electrical tests of insulated conductors not enclosed in a lead sheath, shall be made while immersed in water after an immersion of twelve (12) consecutive hours, if insulated with rubber compound, or if insulated with varnished cambric. It is not necessary to immerse in water insulated conductors enclosed in a lead sheath.

In multiple-conductor cables, without waterproof overall jacket of insulation, no immersion test should be made on finished cables, but only on the individual conductors before assembling.

680 **Dielectric-Strength Tests. Object of Tests.** Dielectric tests are intended to detect weak spots in the insulation and to determine whether the dielectric strength of the insulation is sufficient for enabling it to withstand the voltage to which it is likely to be subjected in service, with a suitable factor of assurance.

The initially-applied voltage must not be greater than the working voltage, and the rate of increase shall not be over 100 per cent in 10 seconds.

681 **Factor of Assurance.** The factor of assurance of wire or cable insulation shall be the ratio of the voltage at which it is tested to that at which it is used.

682 **Test Voltage.** The dielectric strength of wire and cable insulation shall be tested at the factory, by applying an alternating test voltage between the conductor and sheath or water.

683 **The Magnitude and Duration of the Test Voltage** should depend upon the dielectric strength and thickness of the insulation, the length and diameter of the wire or cable, and the assurance factor required, the latter in turn depending upon the importance of the service in which the wire or cable is employed.

684 **The following test voltages** shall apply unless a departure is considered necessary, in view of the above circumstances. Rubber covered wires or cable for voltages up to 7 kv. shall be tested in accordance with the National Electric Code. Standardization for higher voltages for rubber insulated cables is not considered possible at the present time.

Varnished cambric and impregnated paper insulated wires or cables shall be tested at the place of manufacture for five (5) minutes in accordance with the Table XIV below.

TABLE XIV

Recommended Test Kilovolts Corresponding to Operating Kilovolts

Operating kv.	Test kv.	Operating kv.	Test kv.
Below 0.5	2.5*	5	14
0.5	3	10	25
1	4	15	35
2	6.5	20	44
3	9	25	53
4	11.5		

*The minimum thickness of insulation shall be $\frac{1}{16}$ in. (1.6 mm.)

Different engineers specify different thickness of insulation for the same working voltages. Therefore, at the present time the test kv. corresponding to working kv. given in Table XIV are based on the **minimum** thickness of insulation specified by engineers and operating companies.†

685 **The Frequency of the Test Voltage** shall not exceed 100 cycles per second, and should approximate as closely as possible to a sine wave. The source of energy should be of ample capacity.

686 **Where Ultimate Break-Down Tests** are required, these shall be made on samples not more than 6 meters (20 ft.) long. The maximum allowable temperature at which the test is made for the particular type of insulation and the particular working pressure, shall not be greater than the temperature limits given in **§ 677**.

687 **Multiple-Conductor Cables.** Each conductor of a multiple-conductor cable shall be tested against the other conductors connected together with the sheath or water.

INSULATION RESISTANCE

688 **Definition.** The insulation resistance of an insulated conductor is the electrical resistance offered by its insulation, to an impressed voltage tending to produce a leakage of current through the same.

689 **Insulation Resistance** shall be expressed in megohms for a specified length (as for a kilometer, or a mile, or one thousand feet), and shall be corrected to a temperature of 15.5° C. using a temperature coefficient determined experimentally for the insulation under consideration.

690 **Linear Insulation Resistance,** or the insulation resistance of Unit Length, shall be expressed in terms of the megohm-kilometer, or the megohm-mile, or the megohm-thousand-feet.

691 **Megohms Constant.** The Megohms Constant of an insulated conductor shall be the factor "K" in the equation

$$R = K \log_{10} \frac{D}{d}$$

where R = The insulation resistance, in megohms, for a specified unit length.

D = Outside diameter of insulation.

d = Diameter of conductor.

Unless otherwise stated, K will be assumed to correspond to the mile unit of length.

692 **Test.** The apparent insulation resistance should be measured after the dielectric-strength test, measuring the leakage current after a one-minute electrification, with a continuous e.m.f. of from 100 to 500 volts, the conductor being maintained negative to the sheath or water.

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†The Standards Committee does not commit itself to the principle of basing test voltages on working voltages, but it is not yet in possession of sufficient data to base them upon the dimensions and physical properties of the insulation.

693 **Multiple-Conductor Cables.** The insulation resistance of each conductor of a multiple-conductor cable shall be the insulation resistance measured from such conductor to all the other conductors in multiple with the sheath or water.

CAPACITANCE OR ELECTROSTATIC CAPACITY

694 **Capacitance** is ordinarily expressed in microfarads. Linear Capacitance, or Capacitance per unit length, shall be expressed in Microfarads per unit length (kilometer, or mile, or one thousand feet) and shall be corrected to a temperature of 15.5° C.

695 **Microfarads Constant.** The Microfarads Constant of an insulated conductor shall be the factor " K " in the equation

$$C = \frac{K}{\operatorname{Log}_{10} \frac{D}{d}}$$

where C = the capacitance in microfarads per unit length.

D = the outside diameter of insulation.

d = the diameter of conductor.

Unless otherwise stated, K will be assumed to refer to the mile unit of length.

696 **Measurement of Capacitance.** The Capacitance of low-voltage cable, shall be measured by comparison with a standard condenser. For long lengths of high-voltage cables, where it is necessary to know the true capacitance, the measurement should be made at a frequency approximating the frequency of operation.

697 **Paired Cables.** The capacitance shall be measured between the two conductors of any pair, the other wires being connected to the sheath or ground.

698 **Electric Light and Power Cables.** The capacitance of low-voltage cables is generally of but little importance. The capacitance of high-voltage cables should be measured between the conductors, and also between each conductor and the other conductors connected to the lead sheath or ground.

699 **Multiple-Conductor Cables** (not paired). The capacitance of each conductor of a multiple-conductor cable shall be the capacitance measured from such conductor to all of the other conductors in multiple with the sheath or the ground.

STANDARDS FOR SWITCHES AND OTHER CIRCUIT-CONTROL APPARATUS[*]

SWITCHES

720 **The following Rules apply to Switches** of above 600 volts. (For 600 volts and below, see National Electric Code.[†])

721 **Definition.** A switch is a device for making, breaking, or changing connections in an electric circuit.

722 **Rating.**

(a) By amperes to be carried with not more than 30 °C. rise on contacts and current-carrying parts.

(b) By normal voltage of circuit on which it may be used.

723 **Performance and Tests.**

(a) **Heating Test** with rated current applied continuously until temperature is constant; ambient temperature 40 °C.

(b) **Dielectric Test** at 2½ times rated voltage plus 2000. See **§509.**

CIRCUIT BREAKERS

724 **Definition.** A device designed to open a current-carrying circuit without injury to itself. A circuit breaker[‡] may be:

(a) An automatic circuit-breaker, which is designed to trip automatically under any predetermined condition of the circuit, such as an underload or overload of current or voltage.

(b) A manually tripped circuit-breaker, which is designed to be tripped by hand.

Both types of operation may be combined in one and the same device.

725 **Rating.**

(a) By normal current-carrying capacity.

(b) By normal voltage.

(c) By amperes which it can interrupt at normal voltage of the circuit.

726 **Performance and Tests.** The heating test shall be made with normal current. In oil circuit breakers the same oil must be used for heating tests as for rupturing tests. The rise of temperature at the contacts shall not exceed 30 °C. The Rise on tripping solenoids and accessory parts not to exceed 50 °C. Ambient temperature of reference, 40 °C.

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[*] These rules do not apply to magnetically-operated or air-operated switches used for motor control.

[†] By the term "Code" is meant "National Electrical Code" as recommended by the National Fire Protection Association.

[‡] These rules refer only to circuit breakers of above 550 volts. For 550 volts and below, see the National Electric Code.

727 **Dielectric Test.** Same as **§723.**

728 **Rupturing Test** must be made with the current specified under **§725** (c), and at normal voltage.

Note. Although circuit breakers should be considered as devices alone, no account being taken, in the rating, of the system on which they are to be used: yet in applying circuit breakers to any given service, it may be necessary to take into account the system on which they are to be used, with all its characteristics.

Allowances must be made for the reactance, resistance, etc., of the circuit to be controlled, as these have a direct bearing on the maximum current flow.

In some systems it has been found that the pressure rises so high during switching, that higher insulation tests than that specified in **§723** should be given.

FUSES

(For circuits up to and including 600 volts, see National Electric Code)

729 **Definition.** A fuse is an element designed to melt or dissipate at a predetermined current value, and intended to protect against abnormal conditions of current.

Note. (The terminals, tubes, etc. which go with the fuse proper are included in the definition).

730 **Rating.** Fuses shall be rated at the maximum current which they are required to carry continuously, and at the normal voltage of the circuit on which they are designed to be used.

Fuses may be divided into two classes:

(1) Those designed to protect the circuit and apparatus both against short circuit and against definite amounts of overload (*e.g.* fuses of the National Electric Code which open on 25 per cent overload).

(2) Those designed to protect the system only against short circuits; (*e.g.* expulsion fuses, which blow at several times the current which they are designed to carry continuously). The line separating these two classes is not definitely fixed.

731 **Temperature.** Coils or windings (such as accompany fuses of the magnetic blow-out type) should not exceed the limits set for machine coils having the same character of insulation. (See **§§376** to **379**). The highest temperature for the fuse proper should not exceed the safe limit for the material employed (*e.g.* the temperature of the fibre tube of an enclosed fuse should not exceed the safe limit for this material, but an open-link metal fuse may be run at any temperature which will not injure the fuse material; except that no application of the above rule shall contravene the National Electric Code).

732 **Test.** For fuses intended for use on circuits of small capacity, or in protected positions on systems of large capacity, see Nation-

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Note. Complete standardization of these fuses above 600 volts, according to the method of the National Electric Code, is not advisable at this time, but is expected to be accomplished by an eventual extension of the National Electric Code. Until such extension is made, the following definitions and ratings may be followed.

al Electric Code. For large power fuses intended for service similar to that required of circuit breakers, see **§724** to **728**, or the National Electric Code, as far as the latter applies.

LIGHTNING ARRESTERS

733 **Definition.** A lightning arrester is a device for protecting circuits and apparatus against lightning or other abnormal potential rises of short duration.

734 **Rating.** Arresters shall be rated by the voltage of the circuit on which they are to be used.

Lightning arresters may be divided into two classes:

(a) Those intended to discharge for a very short time.

(b) Those intended to discharge for a period of several minutes.

735 **Performance and Tests.** Dielectric Test same as **§723.**

The resistance of the arrester at double potential and also at normal potential, shall be determined by observing the discharge currents through the arrester.

(c) In the case of any arrester using a gap, a test shall be made of the spark potential on either direct-current or 60-cycle a-c. excitation.

(d) The equivalent sphere gap under disruptive discharge shall also be measured, using a considerable quantity of electricity.

(e) The endurance of the arrester to continuous surges shall be tested.

PROTECTIVE REACTORS

736 **Definition.** A reactor (See **§82** and **214**) is a device for protecting circuits by limiting the current flow and localizing the disturbance under short-circuit conditions.

737 **Rating.**

(a) In kilovolt-amperes absorbed by normal current.

(b) By the normal current, frequency and line (delta) voltage for which the reactor is designed.

(c) By the current which the device is required to stand under short-circuit conditions.

738 **Performance and Tests.**

The Heat Test shall be made with normal current and frequency applied until the temperature is constant. The temperature should not exceed the safe limits for the materials employed. See **§§376** to **379.**

739 **Dielectric Test.** 2½ times line voltage plus 2000, for one minute, from conductor to ground.

NOTE. The reactor shall be so designed as to be capable of withstanding, without mechanical injury, rated current at normal frequency, suddenly applied.

RESISTOR OR RHEOSTAT

740 **Definition.** Any device heretofore commonly known as a resistance, used for operation or control. (**§81**) See National Electric Code.

INSTRUMENT TRANSFORMERS

741 **Definition.** An instrument transformer is a transformer for use with measuring instruments, in which the conditions in the primary circuit as to current and voltage are represented with high numerical accuracy in the secondary circuit.

Under this heading and for more general use:

(a) A current transformer is a transformer designed for series connection in its primary circuit with the ratio of transformation appearing as a ratio of currents.

(b) A potential (voltage) transformer is a transformer designed for shunt or parallel connection in its primary circuit, with the ratio of transformation appearing as a ratio of potential differences (voltages).

For further definitions relative to instrument transformers, see **205-207.**

For the dielectric test of potential transformers, see **§500,** and for the dielectric test of current transformers, see **§509.**

Further standards concerning instrument transformers are still under discussion.

STANDARDS FOR ELECTRIC RAILWAYS

DEFINITIONS

760 **Transmission System:** When the current generated for an electric railway is changed in kind or voltage, between the generator and the cars or locomotives, that portion of the conductor system carrying current of a kind or voltage substantially different from that received by the cars or locomotives, constitutes the *transmission system.**

761 **Distribution System:** That portion of the conductor system of an electric railway which carries current of the kind and voltage received by the cars or locomotives, constitutes the *distribution system.**

762 **Substation:** A substation is a group of apparatus or machinery which receives current from a transmission system, changes its kind or voltage, and delivers it to a distribution system.

RATING OF RAILWAY SUBSTATION MACHINERY

763 **Continuous Rating.** The rating of a substation machine shall be the kv-a. output at a stated power factor input, which it will deliver continuously with temperatures or temperature rises not exceeding the limiting values given in Sections **376** and **379** and also fulfilling the other requirements set forth in these rules and summarized in Section **260.**

764 **Momentary Loads.** These machines should be capable of carrying a load of twice their rating for one minute, after a continuous run at rated load, without disqualifying them for continuous service.

765 **Nominal Rating.** Where the continuous rating is inconvenient, the following nominal rating may be used. The nominal rating of a substation machine shall be the kv-a. output at a stated power factor input, which, having produced a constant temperature in the machine may be increased 50 per cent for two hours, without producing temperatures or temperature rises exceeding by more than 5°C. the limiting values given in **§376** and **379.** These machines should be capable of carrying a load of twice their nominal rating for a period of one minute, without disqualifying them for continuous service. The name plate should be marked " nominal rating."

CONDUCTOR AND RAIL SYSTEMS.

766 **Contact Conductors.** That part of the distribution system other than the traffic rails, which is in immediate electrical contact with

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*These definitions are identical in sense, although not in words, with those of the Interstate Commerce Commission, as given in their Classification of Accounts for Electric Railways.

the circuits of the cars or locomotives, constitutes the contact conductors.

767 **Contact Rail:** A rigid contact conductor.

768 Overhead Contact Rail: A contact rail above the elevation of the maximum equipment line.†

769 Third Rail: A contact conductor placed at either side of the track, the contact surface of which is a few inches above the level of the top of the track rails.

770 Center Contact Rail: A contact conductor placed between the track rails, having its contact surface above the ground level.

771 Underground Contact Rail: A contact conductor placed beneath the ground level.

772 Gage of Third Rail: The distance, measured parallel to the plane of running rails, between the gage line of the nearer track rail and the inside gage line of the *contact surface* of the third rail.

773 Elevation of Third Rail: The elevation of the contact-surface of the third rail, with respect to the plane of the tops of running rails.

774 Standard Gage of Third Rails: The gage of third rails shall be not less than 26 inches (66 cm.) and not more than 27 inches (68.6 cm.).

775 Standard Elevation of Third Rails: The elevation of third rails shall be not less than 2¾ inches (70 mm.), and not more than 3½ inches (89 mm.).

776 Third Rail Protection: A guard for the purpose of preventing accidental contact with the third rail.

777 **Trolley Wire:** A flexible contact conductor, customarily supported above the cars.

778 **Messenger Wire or Cable:** A wire or cable running along with and supporting other wires, cables or contact conductors.

A primary messenger is directly attached to the supporting system. A secondary messenger is intermediate between a primary messenger and the wires, cables or contact conductors.

779 **Classes of Construction:** Overhead trolley construction will be classed as *Direct Suspension* and *Messenger or Catenary Suspension*

780 Direct Suspension: All forms of overhead trolley construction in which the trolley wires are attached, by insulating devices, directly to the main supporting system.

781 Messenger or Catenary Suspension: All forms of overhead trolley construction in which the trolley wires are attached, by suitable devices, to one or more messenger cables, which in turn may be carried either in *Simple Catenary, i.e.*, by primary messengers, or in *Compound Catenary, i.e.*, by secondary messengers.

782 Supporting Systems shall be classed as follows:

783 Simple Cross-Span Systems: Those systems having at each support a single flexible span across the track or tracks.

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†The contour which embraces cross-sections of all rolling stock under all normal operating conditions.

784 **Messenger Cross-Span Systems:** Those systems having at each support two or more flexible spans across the track or tracks, the upper span carrying part or all of the vertical load of the lower span.

785 **Bracket Systems:** Those systems having at each support an arm or similar rigid member, supported at only one side of the track or tracks.

786 **Bridge Systems:** Those systems having at each support a rigid member, supported at both sides of the track or tracks.

787 **Standard Height of Trolley Wire on Street and Interurban Railways:** It is recommended that supporting structures shall be of such height that the lowest point of the trolley wire shall be at a height of 18 feet (5.5m.) above the top of rail under conditions of maximum sag, unless local conditions prevent. On trackage operating electric and steam road equipment and at crossings over steam roads, it is recommended that the trolley wire shall be not less than 21 feet (6.4m.) above the top of rail, under conditions of maximum sag.

RAILWAY MOTORS

RATING

800 **Nominal Rating**: The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90 °C. at the commutator, and 75 °C. at any other normally accessible part after one hour's continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature as measured by resistance, shall not exceed 100 °C.*

801 The statement of the nominal rating shall also include the corresponding voltage and armature speed.

802 **Continuous Rating:** The continuous ratings of a railway motor shall be the *inputs* in amperes at which it may be operated continuously at ½, ¾ and full voltage respectively, without exceeding the specified temperature rises (see §805), when operated on stand test with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to

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* This definition differs from that in the 1911 edition of the Rules, principally by the substitution of a kilowatt rating for the horse-power rating and the omission of a reference to a room temperature of 25°C. For the purposes of these Rules the horse-power shall be taken as 746.0 watts. On account of the hitherto prevailing practise of expressing mechanical output in horse-power, it is recommended that, for the present the capacity be expressed both in kilowatts and in horse-power, a double rating, namely,

kw.————approx. equiv. h.p.————

In order to lay stress upon the preferred future basis, it is desirable that on rating plates, the rating in kilowatts shall be shown in larger and more prominent characters than the capacity in horse power.

define the system of ventilation which is used. In case motors are cooled by external blowers, the flow of air on which the rating is based shall be given.

803 **Maximum Input.** The subject of momentary loads for railway motors is under investigation.

TEMPERATURE LIMITATIONS

804 **The allowable temperature** in any part of a motor in service will be governed by the kind of material with which that part is insulated. In view of space limitations, and the cost of carrying dead weight on cars, it is considered good practice to operate railway motors for short periods at higher temperatures than would be advisable in stationary motors. The following temperatures are permissible:

TABLE XV

Operating Temperatures of Railway Motors

Class of Material See §376 to 379.	Maximum Observable Temperature of windings when in continuous service.	
	By Thermometer See §345	By Resistance
A	85	110
B	100	130

For infrequent occasions, due to extreme ambient temperatures, it is permissible to operate at 15° higher temperature.

805 With a view to not exceeding the above temperature limitations, the continuous ratings shall be based upon the **temperature rises** tabulated below:

TABLE XVI

Stand-Test Temperature Rises of Railway Motors*

Class of Material See §376 to 379	Temperature Rises of windings	
	By Thermometer See §345	By Resistance
A	65	85
B	80	105

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*The temperature rise in service may be very different from that on stand test. See § 1104 for relation between stand test and service temperatures, as affected by ventilation.

806 **Field-Control Motors.** The nominal and continuous ratings of field-control motors shall relate to their performance with the operating field which gives the maximum motor rating. Each section of the field windings shall be adequate to perform the service required of it, without exceeding the specified temperature rises.

CHARACTERISTIC CURVES

810 **The Characteristic Curves** of railway motors shall be plotted with the current as abscissas and the tractive effort, speed and efficiency as ordinates. In the case of a-c. motors, the power factor shall also be plotted as ordinates.

811 **Characteristic curves of direct-current motors** shall be based upon full voltage, which shall be taken as 600 volts, or a multiple thereof.

812 **In the case of field-control motors,** characteristic curves shall be given for all operating field connections.

EFFICIENCY AND LOSSES

815 **The efficiency** of railway motors shall be deduced from a determination of the losses enumerated in **§816** to **820.** (See also **§1100** and **1101.**)

816 **The copper loss** shall be determined from resistance measurements corrected to 75° C.

817 **The no-load core loss, brush friction, armature-bearing friction and windage** shall be determined as a total under the following conditions:

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. With the field separately excited, such a voltage shall be applied to the armature terminals as will give the same speed for any given field current as is obtained with that field current when operating at normal voltage under load. The sum of the losses above-mentioned, is equal to the product of the counter-electromotive force and the armature current.

818 The **core loss** in d-c. motors shall be separated from the friction and windage losses above described by measuring the power required to drive the motor at any given speed without gears, by running it as a series motor on low voltage and deducting this loss from the sum of the no-load losses at corresponding speed. (See **§1101** for alternative method).

The friction and windage losses under load shall be assumed to be the same as without load, at the same speed.

The core loss under load shall be assumed as follows:

TABLE XVII

Core Loss in D-C. Railway Motors at Various Loads.

Per cent of Input at Nominal Rating	Loss as Per cent of No-load Core Loss
200	165
150	145
100	130
75	125
50	123
25 and under	122

Note:—With motors designed for field control the core losses shall be assumed as the same for both full and permanent field. It shall be the mean between the no-load losses at full and permanent field, increased by the percentages given in the above Table

819 **The brush-contact resistance loss** to be used in determining the efficiency, may be obtained by assuming that the sum of the drops at the contact surfaces of the positive and negative brushes is three volts.

820 The losses in gearing and axle bearings for single-reduction single-geared motors, varies with type, mechanical finish, age and lubrication The following values, based on accumulated tests, shall be used in the comparison of single-reduction single-geared motors.

TABLE XVIII

Losses in Axle Bearings and Single-Reduction Gearing of Railway Motors.

Per Cent of Input at Nominal Rating	Losses as Per Cent of Input
200	3.5
150	3.0
125	2.7
100	2.5
75	2.5
60	2.7
50	3.2
40	4.4
30	6.7
25	8.5

Note:—Further investigation may indicate the desirability of giving separate values of the losses for full and tapped fields, or low- and high-speed motors.

ELECTRIC LOCOMOTIVES

830 **Rating.** Locomotives shall be rated in terms of the weight on drivers, nominal one-hour tractive effort, continuous tractive effort and corresponding speeds.

831 **Weight on Drivers.** The weight on drivers, expressed in pounds, shall be the sum of the weights carried by the drivers and of the drivers themselves.

832 **Nominal Tractive Effort:** The nominal tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers, when the motors are operating at their nominal (one-hour) rating.

833 **Continuous Tractive Effort.** The continuous tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their full-voltage continuous rating, as indicated in **§802**.

In the case of locomotives operating on intermittent service, the continuous tractive effort may be given for ½ or ¾ voltage, but in such cases the voltage shall be clearly specified.

834 **Speed:** The rated speed, expressed in miles per hour, shall be that at which the continuous tractive effort is exerted.

See also Appendix II on Additional Standards for Railway Motors.

RATING OF AUTOMOBILE PROPULSION MOTORS AND GENERATORS

(ROAD VEHICLES)

835 **Continuous Rating.** Automobile propulsion motors and generators shall be given a continuous rating, expressed in kilowatts output available at the shaft at specified speed. The machines shall be able to operate continuously at their rated outputs without exceeding any of the limitations referred to in **§260**.

836 **Short-Time Rating.** Owing to the variety of services which road vehicles are called upon to perform, no single standard period for short-time ratings is recommended.

837 **Nominal Rating.** No special nominal rating is required for automobile propulsion motors or generators.

838 **Temperature Rises.** Owing to space limitations and the cost of carrying dead weight on automobiles, it is considered good practice to operate the propulsion machinery at higher temperatures than would be advisable in stationary machines. The rating of automobiles motors and generators shall be based upon temperature rise, on a stand test and with motor covers arranged as in service, fifteen degrees by thermometer or twenty-five degrees by resistance, above those of **§379**.

839 **Efficiency and Losses.** Unless otherwise specified the efficiency of automobile propulsion machines shall be based upon the output at the shaft, using conventional losses as tabulated in **§440**. When such machines are of low voltage, the great influence of brush-contact losses on the efficiency requires that these losses be determined experimentally for the type of brush used.

ILLUMINATION AND PHOTOMETRY

The following Sections, **850** to **895**, are abstracts from the rules of the Nomenclature and Standards Committee of the Illuminating Engineering Society. They are here included by permission.

850 **Luminous Flux** is radiant power evaluated according to its capacity to produce the sensation of light.

851 **The stimulus coefficient** K_λ for radiation of a particular wave-length, is the ratio of the luminous flux to the radiant power producing it.

852 **The mean value of the stimulus coefficient,** K_m, over any range of wave-lengths, or for the whole visible spectrum of any source, is the ratio of the total luminous flux (in lumens) to the total radiant power (in ergs per second, but more commonly in watts).

853 **The luminous intensity** of a point source of light is the solid angular density of the luminous flux emitted by the source in the direction considered; or it is the flux per unit solid angle from that source.

Defining equation:

Let I be the intensity, F the flux and ω the solid angle.

Then if the intensity is uniform,

$$I = \frac{F}{\omega},$$

854 **Illumination,** on a surface, is the luminous flux-density over that surface, or the flux per unit of intercepting area.

Defining equation:

Let E be the illumination and S the area of the intercepting surface.

Then when uniform,

$$E = \frac{F}{S},$$

855 **Candle,** the unit of luminous intensity maintained by the National Laboratories of France, Great Britain, and the United States.[1]

856 **Candle-power,** luminous intensity expressed in candles.

857 **Lumen,** the unit of luminous flux, equal to the flux emitted in a unit solid angle (steradian) by a point source of one candle-power.[2]

858 **Lux,** a unit of illumination equal to one lumen per square meter. The C. G. S. unit of illumination is one lumen per square centimeter. For this unit Blondel has proposed the name "Phot." One millilumen per square centimeter (milliphot) is a practical derivative of

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[1] This unit, which is used also by many other countries, is frequently referred to as the international candle.

the C. G. S. system. One foot-candle is one lumen per square foot and is equal to 1.0764 milliphots.

860 **Specific luminous radiation,** the luminous flux-density emitted by a surface, or the flux emitted per unit of emissive area. It is expressed in lumens per square centimeter.

Defining equation:

Let E' be the specific luminous radiation.

For surfaces obeying Lambert's cosine law of emission.

$$E' = \pi b_0.$$

863 **The Lambert, the C. G. S. Unit of Brightness,** the brightness of a perfectly diffusing surface radiating or reflecting one lumen per square centimeter. This is equivalent to the brightness of a perfectly diffusing surface having a coefficient of reflection equal to unity and illuminated by one phot.

864 **For most purposes, the millilambert** (0.001 lambert) is the preferable practical unit. A perfectly diffusing surface emitting one lumen per square foot will have a brightness of 1.076 millilamberts.

865 **Brightness expressed in candles per square centimeter** may be reduced to Lamberts by multiplying by π.

Brightness expressed in candles per square inch may be reduced to foot-candle brightness, by multiplying by the factor $144\,\pi = 452$.

Brightness expressed in candles per square inch may be reduced to lamberts by multiplying by $\pi/6.45 = 0.4868$.

In practise, no surface obeys exactly Lambert's cosine law of emission; hence the brightness of a surface in lamberts is, in general not numerically equal to its specific luminous radiation in lumens per square centimeter.

866 **Coefficient of reflection,** the ratio of the total luminous flux reflected by a surface to the total luminous flux incident upon it. It is a simple numeric. The reflection from a surface may be regular, diffuse or mixed. In perfect regular reflection, all of the flux is reflected from the surface at an angle of reflection equal to the angle of incidence. In perfect diffuse reflection, the flux is reflected from the surface in all directions, in accordance with Lambert's cosine law. In most practical cases, there is a superposition of regular and diffuse reflection.

867 **Coefficient of regular reflection** is the ratio of the luminous flux reflected regularly to the total incident flux.

868 **Coefficient of diffuse reflection** is the ratio of the luminous flux reflected diffusely to the total incident flux.

Defining equation:

Let m be the coefficient of reflection (regular or diffuse).

Then, for any given portion of the surface,

$$m = \frac{E'}{E}$$

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[2] A uniform source of one candle emits 4π lumens.

869 **Lamp,** a generic term for an artificial source of light.

870 **Primary luminous standard,** a recognized standard luminous source reproducible from specifications.

871 **Representative luminous standard,** a standard of luminous intensity adopted as the authoritative custodian of the accepted value of the unit.

872 **Reference standard,** a standard calibrated in terms of the unit from either a primary or representative standard and used for the calibration of working standards.

873 **Working standard,** any standardized luminous source for daily use in photometry.

874 **Comparison lamp,** a lamp of constant but not necessarily known candle-power, against which a working standard and test lamps are successively compared in a photometer.

875 **Test lamp,** in a photometer,—a lamp to be tested.

876 **Performance curve,** a curve representing the behavior of a lamp in any particular (candle-power, consumption, etc.) at different periods during its life.

877 **Characteristic curve,** a curve expressing a relation between two variable properties of a luminous source, as candle-power and volts, candle-power and rate of fuel consumption, etc.

878 **Horizontal Distribution Curve.** A polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane perpendicular to the axis of the unit, and with the unit at the origin.

879 **Vertical Distribution Curve.** A polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane passing through the axis of the unit, and with the unit at the origin. Unless otherwise specified, a vertical distribution curve is assumed to be an *average* vertical distribution curve, such as may in many cases be obtained by rotating the unit about its axis and measuring the average intensities at the different elevations. It is recommended that in vertical distribution curves, angles of elevation shall be counted positively from the nadir as zero, to the zenith as 180 degrees. In the case of incandescent lamps, it is assumed that the vertical distribution curve is taken with the tip downward.

880 **Mean horizontal candle-power** of a lamp,—the average candle-power in the horizontal plane passing through the luminous center of the lamp.

It is here assumed that the lamp (or other light source) is mounted in the usual manner, or, as in the case of an incandescent lamp, with its axis of symmetry vertical.

881 **Mean spherical candle-power** of a lamp,—the average candle-power of a lamp in all directions in space. It is equal to the total luminous flux of the lamp, in lumens, divided by 4π.

882 **Mean hemispherical candle-power** of a lamp (upper or lower),—the average candle-power of a lamp in the hemisphere considered. It is equal to the total luminous flux emitted by the lamp, in that hemisphere, divided by 2π.

883 **Mean zonal candle-power** of a lamp,—the average candle-power of a lamp over the given zone. It is equal to the total luminous flux emitted by the lamp in that zone, divided by the solid angle of the zone.

884 **Spherical reduction factor** of a lamp,—the ratio of the mean spherical to the mean horizontal candle-power of the lamp.[3]

885 **Photometric Tests** in which the results are stated in candle-power should be made at such a distance from the source of light that the latter may be regarded as practically a point. Where tests are made in the measurement of lamps with reflectors, the results should always be given as "apparent candle-power" at the distance employed, which distance should always be specifically stated.

886 **The output of all illuminants** should be expressed in lumens.

887 **Illuminants should be rated** upon a lumen basis instead of a candle-power basis.

888 **The specific output of electric lamps** should be stated in lumens per watt; and the specific output of illuminants depending upon combustion should be stated in lumens per b.t.u. per hour. The use of the term "efficiency" in this connection should be discouraged.

When auxiliary devices are necessarily employed in circuit with a lamp, the input should be taken to include both that in the lamp and that in the auxiliary devices. For example, the watts lost in the ballast resistance of an arc lamp are properly chargeable to the lamp.

889 **The Specific Consumption** of an electric lamp is its watt consumption per lumen. "Watts per candle" is a term used commercially in connection with electric incandescent lamps, and denotes watts per mean horizontal candle-power.

890 **Life Tests. Electric Incandescent Lamps** of a given type may be assumed to operate under comparable conditions only when their lumens per watt consumed are the same. Life-test results, in order to be compared, must be either conducted under, or reduced to, comparable conditions of operation.

891 **In Comparing Different Luminous Sources,** not only should their candle-power be compared, but also their relative form, brightness, distribution of illumination and character of light.

892 **Lamp Accessories. A reflector** is an appliance, the chief use of which is to redirect the luminous flux of a lamp in a desired direction or directions.

893 **A Shade** is an appliance, the chief use of which is to diminish or to interrupt the flux of a lamp in certain directions, where such flux is not desirable. The function of a shade is commonly combined with that of a reflector.

894 **A Globe** is an enclosing appliance of clear or diffusing materials, the chief use of which is either to protect the lamp, or to diffuse its light.

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[3] In the case of a uniform point-source, this factor would be unity, and for a straight cylindrical filament obeying the cosine law it would be $\pi/4$.

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TABLE XIX.

Photometric Units and Abbreviations.

Photometric quantity	Name of unit	Abbreviations, Symbols and defining equations
1. Luminous flux	Lumen	$F.\ \Psi$
2. Luminous intensity	Candle	$I = \frac{dF}{d\omega}, \Gamma = \frac{d\Psi}{d\omega}$, cp.
3. Illumination	Phot., foot-candle, lux	$E = \frac{dF}{dS} = \frac{I}{r^2}\cos\theta.\beta$
4. Exposure	Phot-second	$t\ E$
5. Brightness	Apparent candles per sq. cm. Apparent candles per sq. in.	$b = \frac{dI}{dS\ \cos\ \theta}$
	Lambert	$L = \frac{dF}{dS}$
6. Normal brightness	Candles per sq. cm. Candles per sq. in.	$b_0 = \frac{dI}{dS}$
7. Specific luminous radiation	Lumens per sq. cm. Lumens per sq. in.	$E' = \pi b_0 \beta'$
8. Coefficient of reflection	—	$m = \frac{E'}{E}$
9. Mean spherical candlepower		scp
10. Mean lower hemispherical candlepower		lcp
11. Mean upper hemispherical candlepower		ucp
12. Mean zonal candlepower		zcp

13. 1 lumen is emitted by 0.07958 spherical cp.
14. 1 spherical candlepower emits 12.57 lumens.
15. 1 lux = 1 lumen incident per square meter = 0,0001 phot = 0.1 milliphot.
16. 1 phot = 1 lumen incident per sq. cm. = 10.000 lux = 1000 milliphot.
17. 1 milliphot = 0.001 phot = 0.929 foot-candle.
18. 1 foot-candle = 1 lumen incident per square foot = 1.076 milliphot = 10.76 lux.
19. 1 lambert = 1 lumen emitted per square centimeter.*
20. 1 millilambert = 0.001 lambert.
21. 1 lumen, emitted, per square foot* = 1.076 millilambert.
22. 1 millilambert = 0.929 lumen, emitted, per square foot*.
23. 1 lambert = 0.3183 candle per sq. cm. = 2.054 candles per sq. in.
24. 1 candle per sq. cm. = 3.1416 lamberts.
25. 1 candle per sq. in. = 0.4868 lamberts = 486.8 millilamberts.

***Perfect diffusion assumed.**

STANDARDS FOR TELEPHONY AND TELEGRAPHY

910 After careful consideration, it does not seem that the time is yet ripe for a formal standardization of terms and definitions used in telephony and telegraphy. Many of the terms commonly employed are used in more than a single way, and conversely, many pieces of apparatus and many constants which are essentially identical from a physical standpoint have been and are known by more than one designation.

911 **Damping of a Circuit.** The damping, at a given point, in a circuit from which the source of energy has been withdrawn, is the progressive diminution in the effective value of electromotive force and current at that point resulting from the withdrawal of electrical energy.

912 **Damping Constant.** The damping constant of a circuit depends upon the ratio of the dissipative to the reactive component of its impedance or admittance.

Applied to the admittance of a condenser or other simple circuit having capacity reactance, the damping constant for a harmonic electromotive force of given frequency is the ratio of the conductance of the condenser or simple circuit at that frequency, to twice the capacity of the condenser at the same frequency.

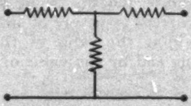
Applied to the reactance of a coil or other simple circuit having inductive reactance, the damping constant for a harmonic current of given frequency is the ratio of the resistance of the coil or circuit at that frequency, to twice the inductance at the same frequency.

913 **Equivalent Circuit.** An equivalent circuit is a simple network of series and shunt impedances, which, at a given frequency, is the approximate electrical equivalent of a complex network at the same frequency and under steady-state conditions.

NOTE: As ordinarily considered, the simple networks as defined are the electrical equivalents of complex networks only with respect to definite pairs of terminals, and only as to sending-end impedances, and total attenuation. A further requirement is that the only connections between the pairs of terminals are those through the network itself.

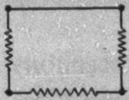
914 **" T " Equivalent Circuit.** A " T " equivalent circuit is a triple-star or " Y " connection of three impedances externally equivalent to a complex network.

Symbol:



915 **"U" Equivalent Circuit.** A "U" equivalent circuit is a delta connection of three impedances externally equivalent to a complex network. It is also called a "Π" equivalent circuit.

Symbol:



IMPEDANCE

916 **Mutual Impedance.** The mutual impedance, for alternating currents, between a pair of terminals and a second pair of terminals of a network, under any given condition, is the negative vector ratio of the electromotive force produced between either pair of terminals on open circuit, to the current flowing between the other pair of terminals.

917 **Self Impedance.** The self impedance between a pair of terminals of a network, under any given condition, is the vector ratio of the electromotive force applied across the terminals to the current produced between them.

LINE CHARACTERISTICS

918 **Characteristic Impedance.** The characteristic impedance of a line is the ratio of the applied electromotive force to the resulting steady-state current upon a line of infinite length and uniform structure, or of periodic recurrent structure.

Note: In telephone practice, the terms (1) line impedance, (2) surge impedance, (3) iterative impedance, (4) sending-end impedance, (5) initial sending-end impedance, (6) final sending-end impedance, (7) natural impedance and (8) free impedance, have apparently been more or less indefinitely and indiscriminately used as synonyms with what is here defined as "characteristic impedance."

919 **Sending-End Impedance.** The sending-end impedance of a line is the vector ratio of the applied electromotive force to the resulting steady-state current at the point where the electromotive force is applied.

Note: See note under "Characteristic Impedance." In case the line is of infinite length of uniform structure or of periodic recurrent structure, the sending-end impedance and the characteristic impedance are the same.

920 **Propagation Constant.** The propagation constant per unit length of a uniform line, or per section of a line of periodic recurrent structure, is the natural logarithm of the vector ratio of the steady-state currents at various points separated by unit length in a uniform line of infinite length, or at successive corresponding points in a line of recurrent structure of infinite length. The ratio is determined by dividing the value of the current at the point nearer the transmitting end by the value of the current at the point more remote.

921 **Attenuation Constant.** The attenuation constant is the real part of the propagation constant.

922 **Wave-Length Constant.** The wave-length constant is the imaginary part of the propagation constant.

LINE CIRCUITS

930 **Ground-Return Circuit.** A ground-return circuit is a circuit consisting of one or more metallic conductors in parallel, with the circuit completed through the earth.

931 **Metallic Circuit.** A metallic circuit is a circuit of which the earth forms no part.

932 **Two-Wire Circuit.** A two-wire circuit is a metallic circuit formed by two paralleling conductors insulated from each other.

933 **Superposed Circuit.** A superposed circuit is an additional circuit obtained from a circuit normally required for another service, and in such a manner that the two services can be given simultaneously without mutual interference.

934 **Phantom Circuit.** A phantom circuit is a superposed circuit, each side of which consists of the two conductors of a two-wire circuit in parallel.

935 **Side Circuit.** A side circuit is a two-wire circuit forming one side of a phantom circuit.

936 **Non-Phantomed Circuit.** A non-phantomed circuit is a two-wire circuit, which is not arranged for use as the side of a phantom circuit.

937 **Simplexed Circuit.** A simplexed circuit is a two-wire telephone circuit, arranged for the super-position of a single ground-return signalling circuit-operating over the wires in parallel.

NOTE: In view of the use of the term "Simplex Operation" in telegraph practice, it is felt that the designation "Simplexed Circuit" as applied to the arrangement described is not a happy one.

938 **Composited Circuit.** A composited circuit is a two-wire telephone circuit, arranged for the superposition on each of its component metallic conductors, of a single independent ground-return signalling circuit.

939 **Quadded or Phantomed Cable.** A quadded or phantomed cable is a cable adapted for the use of phantom circuits.

NOTE: The type of cable here defined has frequently been designated as "Duplex Cable"—a term which is objectionable., both on account of its lack of description and its widely different use in telegraph practice.

LOADING

950 **Loaded Line.** A loaded line is one in which the normal inductance of the circuit has been altered for the purpose of increasing its transmission efficiency for one or more frequencies.

951 **Series Loaded Line.** A series loaded line is one in which the normal inductance has been altered by inductance serially applied.

952 **Shunt Loaded Line.** A shunt loaded line is one in which the normal inductance of the circuit has been altered by inductance applied in shunt across the circuit.

953 **Continuous Loading.** A continuous loading is a series loading in which the added inductance is uniformly distributed along the conductors.

954 **Coil Loading.** A coil loading is one in which the normal inductance is altered by the insertion of lumped inductance in the circuit at intervals. This lumped inductance may be applied either in series or in shunt.

NOTE: As commonly understood, coil loading is a series loading, in which the lumped inductance is applied at uniformly spaced recurring intervals

955 **Microphone.** A contact device designed to have its electrical resistance directly and materially altered by slight differences in mechanical pressure.

956 **Relay.** A relay is a device by means of which contacts in one circuit are operated under the control of electrical energy in the same or other circuits.

957 **Resonance.** Resonance of a harmonic alternating current of given frequency, in a simple series circuit, containing resistance, inductance and capacity, is the condition in which the positive reactance of the inductance is numerically equal to the negative reactance of the capacity. Under these conditions, the current flow in the circuit with a given electromotive force is a maximum.

958 **Retardation Coil.** A retardation coil is a reactor (reactance coil) used in a circuit for the purpose of selectively reacting on currents which vary at different rates.

NOTE: In telephone and telegraph usage, the terms "impedance coil," "inductance coil," choke coil" and "reactance coil" are sometimes used in place of the term "retardation coil."

959 **Skin Effect.** Skin effect is the phenomenon of the non-uniform distribution of current throughout the cross-section of a linear conductor, occasioned by variations in the intensity of the magnetic field due to the current in the conductor.

960 **Telephone Receiver.** A telephone receiver is an electrically operated device, designed to produce sound waves or vibrations which correspond in form to the electromagnetic waves or vibrations actuating it.

961 **Telephone Transmitter.** A telephone transmitter is a sound-wave or vibration-operated device designed to produce electromagnetic waves or vibrations which correspond in form to the sound waves or vibrations actuating it.

962 **The Coefficient of Coupling of a Transformer.** The coefficient of coupling of a transformer at a given frequency, is the vector ratio of the mutual impedance between the primary and secondary of the transformer, to the square root of the product of the self-impedances of the primary and of the secondary.

963 **Repeating Coil.** A term used in telephone practice meaning the same as transformer, and ordinarily a transformer of unity ratio.

APPENDIX I.

STANDARDS FOR RADIO COMMUNICATION

The following Sections **1000** to **1033** have been abstracted from the report of the Standardization Committee of the Institute of Radio Engineers, and are here included by permission as an Appendix, until further revised. For full particulars, see the I.R.E. Standardization Committee report.

1000 Acoustic Resonance Device. One which utilizes, in its operation, resonance to the audio frequency of the received signals.

1001 Antenna. A system of conductors designed for radiating or absorbing the energy of electromagnetic waves.

1002 Atmospheric Absorption. That portion of the total loss of radiated energy due to atmospheric conductivity.

1003 Audio Frequencies. The frequencies corresponding to the normally audible vibrations. These are assumed to lie below 10,000 cycles per second.

1004 Capacitive Coupler. An apparatus which, by electric fields, joins portions of two radio frequency circuits, and which is used to transfer electrical energy between these circuits through the action of electric forces.

1005 Coefficient of Coupling (Inductive). The ratio of the effective mutual inductance of two circuits to the square root of the product of the effective self-inductances of each of these circuits.

1006 Direct Coupler. A coupler which magnetically joins two circuits having a common conductive portion.

1007 Counterpoise. A system of electrical conductors forming one portion of a radiating oscillator, the other portion of which is the antenna. In land stations a counterpoise forms a capacitive connection to ground.

1008 A Damped Alternating Current is an alternating current whose amplitude progressively diminishes.

1009 The Damping Factor of an exponentially damped alternating current is the product of the logarithmic decrement and the frequency.

Let I_0 = initial amplitude
I_t = amplitude at the time t
ϵ = base of Napierian logarithms
a = damping factor

Then: $I_t = I_0 \, \epsilon^{-at}$

1010 Detector. That portion of the receiving apparatus which, connected to a circuit carrying currents of radio frequency, and in conjunction with a self-contained or separate indicator, translates the radio frequency energy into a form suitable for operation of the indicator. This translation may be effected either by the conversion of the radio frequency energy, or by means of the control of local energy by the energy received.

1011 **Electromagnetic Wave.** A periodic electromagnetic disturbance progressing through space.

1012 **Forced Alternating Current.** A current, the frequency and damping of which are equal to the frequency and damping of the exciting electromotive force.

1013 **Free Alternating Current.** The current following any electromagnetic disturbance in a circuit having capacity, inductance, and *less* than the critical resistance.

1014 **Critical Resistance of a Circuit.** That resistance which determines the limiting condition at which the oscillatory discharge of a circuit passes into an aperiodic discharge.

1015 **Group Frequency.** The number per second of periodic changes in amplitude or frequency of an alternating current.

NOTE 1. Where there is more than one periodically recurrent change of amplitude or frequency, there is more than one group frequency present.

NOTE 2. The term "group frequency" replaces the term "spark frequency."

1016 **Inductive Coupler.** An apparatus which, by magnetic forces, joins portions of two radio frequency circuits and is used to transfer electrical energy between these circuits, through the action of these magnetic forces.

1017 **Linear Decrement of a Linearly Damped Alternating Current** is the difference of successive current amplitudes in the same direction, divided by the larger of these amplitudes.

Let: I_n and I_{n+1} be successive current amplitudes in the same direction, of a linearly-damped alternating current.

Then: The linear decrement, $b = \frac{I_n - I_{n+1}}{I_n}$

Also: $I_t = I_0 \, (1 - bft)$

Where: I_0 = initial current amplitude

I_t = current amplitude at time t

f = frequency of alternating current

1018 **Logarithmic Decrement** of an exponentially damped alternating current is the logarithm of the ratio of successive current amplitudes in the same direction.

NOTE: Logarithmic decrements are standard for a complete period or cycle.

Let: I_n and I_{n+1} be successive current amplitudes in the same direction.

d = logarithmic decrement

Then: $d = \log_e \frac{I_n}{I_{n+1}}$

1019 **Radio Frequencies.** The frequencies higher than those corresponding to the normally audible vibrations, which are generally taken as 10,000 cycles per second. See also Audio Frequencies.

NOTE: It is not implied that radiation cannot be secured at lower frequencies and the distinction from audio frequencies is merely one of definition based on convenience

1020 **Resonance** of a circuit to a given exciting alternating e.m.f. is that condition due to variation of the inductance or capacity in which the resulting effective current (or voltage) in that circuit is a maximum.

1024 **A Standard Resonance Curve** is a curve the ordinates of which are the ratios of the square of the current at any frequency to the square of the resonant current, and the abscissas are the ratios of the corresopnding wave length to the resonant wave length; the abscissas and ordinates having the same scale.

1026 **Sustained Radiation** consists of waves radiated from a conductor in which an alternating current flows.)

1027 **Tuning.** The process of securing the maximum indication by adjusting the time period of a driven element. (See Resonance.)

1028 **A Wave-Meter,** is a radio frequency measuring instrument, calibrated to read wave lengths.

1030 **Decremeter.** An instrument for measuring the logarithmic decrement of a circuit or of a train of electromagnetic waves.

1031 **Attenuation, Radio.** The decrease with distance from the radiating source, of the amplitude of the electric and magnetic forces accompanying (and constituting) an electromagnetic wave.

1032 **Attenuation, Coefficient of (Radio).** The coefficient, which, when multiplied by the distance of transmission through a uniform medium, gives the natural logarithm of the ratio of the amplitude of the electric or magnetic forces at that distance, to the initial value of the corresponding quantities.

1033 **Coupler.** An apparatus which is used to transfer radio-frequency energy from one circuit to another by associating portions of these circuits.

APPENDIX II.

ADDITIONAL STANDARDS FOR RAILWAY MOTORS

1100 In comparing projected motors, and in case it is not possible or desirable to make tests to determine mechanical losses, the following values of these losses, determined from the averages of many tests over a wide range of sizes of single-reduction single-geared motors, will be found useful, as approximations. They include axle-bearing, gear, armature-bearing, brush-friction, windage, and stray-load losses.

TABLE XX
Approximate Losses in D-C. Railway Motors.

Input in per cent of that at nominal rating	Losses as per cent of input
100 or over	5.0
75	5.0
60	5.3
50	6.5
40	8.8
30	13.3
25	17.0

1101 The core loss of railway motors is sometimes determined by separately exciting the field, and driving the armature of the motor to be tested, by a separate motor having known losses and noting the differences in losses between driving the motor light at various speeds and driving it with various field excitations.

1102 **Selection of Motor For Specified Service**

The following information relative to the service to be performed, is required, in order that an appropriate motor may be selected.

(a) Weight of total number of cars in train (in tons of 2000 lb.) exclusive of electrical equipment and load.
(b) Average weight of load and durations of same, and maximum weight of load and durations of same.
(c) Number of motor cars or locomotives in train, and number of trailer cars in train.
(d) Diameter of driving wheels.
(e) Weight on driving wheels, exclusive of electrical equipment.
(f) Number of motors per motor car.
(g) Voltage at train with power on the motors—average, maximum and minimum.

(h) Rate of acceleration in mi. per. hr. per second.
(i) Rate of braking (retardation in m. per hr. per second).
(j) Speed limitations, if any (including slowdowns).
(k) Distances between stations.
(l) Duration of station stops.
(m) Schedule speed including station stops in m.p.h.
(n) Train resistance in pounds per ton of 2000 pounds at stated speeds.
(o) Moment of inertia of revolving parts, exclusive of electrical equipment.
(p) Profile and alignment of track.
(q) Distance coasted as a per cent of the distance between station stops.
(r) Time of layover at end of run, if any.

1103 **Stand-Test Method of Comparing Motor Capacity with Service Requirements:** When it is not convenient to test motors under actual specific service conditions, recourse may be had to the following method of determining temperature rise.

1104 The essential motor losses affecting temperatures in service are those in the motor windings, core and commutator. The mean service conditions may be expressed, as a close approximation, in terms of that continuous current and core loss which will produce the same losses and distribution of losses as the average in service.

A stand test with the current and voltage which will give losses equal to those in service, will determine whether the motor has sufficient capacity to meet the service requirements. In service, the temperature rise of an enclosed motor (**§164**), well exposed to the draught of air incident to a moving car or locomotive, will be from 75 to 90 percent (depending upon the character of the service) of the temperature rise obtained on a stand test with the motor completely enclosed and with the same losses. With a ventilated motor (**§165** and **§167**), the temperature rise in service will be 90 to 100 per cent of the temperature rise obtained on a stand test with the same losses.

1105 In making a stand test to determine the temperature rise in a specific service, it is essential in the case of a self-ventilated motor (**§ 167**), to run the armature at a speed which corresponds to the schedule speed in service. In order to obtain this speed it may be necessary, while maintaining the same total armature losses, to change somewhat the ratio between the I^2R and core-loss components.

1106 **Calculation for Comparing Motor Capacity with Service Requirements.** The heating of a motor should be determined, wherever possible, by testing it in service, or with an equivalent duty cycle. When the service or equivalent duty-cycle tests are not practicable, the ratings of the motor may be utilized as follows to determine its temperature rise.

1107 The motor losses which affect the heating of the windings are as stated above, those in the windings and in the core. The former are proportional to the square of the current. The latter vary with the voltage and current, according to curves which can be supplied by the manufacturers. The procedure is therefore as follows:

1108 (a) Plot a time-current curve, a time-voltage curve, and a time-core loss curve for the duty cycle which the motor is to perform, and calculate from these the root-mean-square current and the average core loss.

1109 (b) If the calculated r.m.s. service current exceeds the continuous rating, when run with average service core loss and speed, the motor is not sufficiently powerful for the duty cycle contemplated.

1110 (c) If the calculated r.m.s. service current does not exceed the continuous rating, when run with average service core loss and speed, the motor is ordinarily suitable for the service. In some cases, however, it may not have sufficient thermal capacity to avoid excessive temperature rises during the periods of heavy load. In such cases a further calculation is required, the first step of which is to compute the equivalent voltage which, with the r.m.s. current, will produce the average core-loss. Having obtained this, determine, as follows, the temperature rise due to the r.m.s. service current and equivalent voltage.

Let

$$\left.\begin{aligned} t &= \text{temperature rise}\\ p_0 &= I^2R \text{ loss, kw.}\\ p_c &= \text{core loss, kw.}\end{aligned}\right\}\text{ with r.m.s. service current, and equivalent service voltage.}$$

$$\left.\begin{aligned} T &= \text{temperature rise}\\ P_0 &= I^2R \text{ loss, kw.}\\ P_c &= \text{core loss, kw.}\end{aligned}\right\}\text{ with continuous load current corresponding to the equivalent service voltage.}$$

Then

$$t = T\,\frac{p_0 + p_c}{P_0 + P_c}\text{, approximately.}$$

1111 (d) The thermal capacity of a motor is approximately measured by the ratio of the electrical loss in kw. at its nominal (one-hour) capacity, to the corresponding maximum observable temperature rise during a one hour test starting at ambient temperature.

1112 (e) Consider any period of peak load and determine the electrical losses in kilowatt-hours during that period from the *electrical* efficiency curve. Find the excess of the above losses over the losses with r.m.s. service current and equivalent voltage. The excess loss, divided by the co-efficient of thermal capacity, will equal the extra temperature rise due to the peak load. This temperature rise added to that due to the r.m.s. service current, and equivalent voltage, gives the total temperature rise. If the total temperature rise in any such period exceeds the safe limit, the motor is not sufficiently powerful for the service.

1113 (f) If the temperature reached, due to the peak loads, does not exceed the safe limit, the motor may yet be unsuitable for the service, as the peak loads may cause excessive sparking and dangerous mechanical stresses. It is, therefore, necessary to compare the peak loads with the short-period overload capacity. If the peaks are also within the capacity of the motor, it may be considered suitable for the given duty cycle.

APPENDIX III.

BIBLIOGRAPHY OF LITERATURE RELATING TO ELECTRICAL ENGINEERING STANDARDIZATION

Engineering Manual of the American Electric Railway Engineering Association.

Standardization Rules of the Electric Power Club.

Report of the Committee on Standardization of the Institute of Radio Engineers.

National Electric Code.

Meter Code—Code for Electricity Meters of the A. E. I. C. and N. E. L. A.

Standardization Reports of the Association of Railway Electrical Engineers.

Publications of American Society for Testing Materials.

The U. S. Bureau of Standards' various publications including Circulars 15, 22, 23, 29, 31, 34, and 37.

Reports of Committee on Nomenclature and Standards of Illuminating Engineering Society.

National Electric Light Association.

American Institute of Electrical Engineers, Specifications.

FOREIGN PUBLICATIONS.

Publications of the Engineering Standards Committee of Great Britain.

Institution of Electrical Engineers, London, Wiring Rules and other publications.

Verband Deutscher Elektrotechniker.

British Electrical and Allied Manufacturers' Association, Reports ef the

INTERNATIONAL PUBLICATIONS.

Publications of the International Electrotechnical Commission.

INDEX.

A

SECTION

Abbreviations.......90, 895
Acceleration Due to Gravity, Symbol and Abbreviation....... 90
Acoustic Resonance Device, defined.. 1000
Active Component of Current or Voltage....... 21
Acyclic Machine, defined....... 141
Adjustable-Speed Motors....... 153
Adjustable-Speed Motors, defined 153
Adjustable Varying Speed Motors, defined....... 154
Admittance, Symbols....... 90
A. I. E. E. Rating....... 264
Air-Blast Transformers, Temperature Correction....... 321
Air-Density Correction for Sphere-Gap 541
Alternating-Current Apparatus, Efficiency of....... 430
Alternating-Current Calculations...... 12
Alternating-Current Commutating Machines....... 131
Alternating Current, Convention for Vectors....... 20
Alternating Current, Damped.......1008
Alternating Current, defined 4,12, 1012,1013
Alternating Current, Forced.......1012
Alternating Current, Free.......1013
Alternator, defined.......134, 135
Alternator, Inductor, defined....... 136
Alternator, Polyphase, defined....... 135
Alternators, Expression of Rating.... 275
Alternators, Variation in,.......66, 67
Altitude, correction for....... 308
Ambient Temperature....... 303
Ambient Temperature, deviation from, ... 320, 321
Ambient Temperature for Machines partly below floor line....... 319
Ambient Temperature for Testing.... 307
Ambient Temperature from an Idle Unit....... 318
Ambient Temperature, Measurement of.......314, 315
Ambient Temperature of Reference for Air....... 305
Ambient Temperature of Reference for Water....... 309
Ambient Temperature, Rotating Machines, Forced Draft....... 311
Ambient Temperatures upon which Permissible Rises are Based...... 306
American Wire Gage....... 652

SECTION

Ammeter....... 226
Amortisseur Windings, temperature of 388
Angular Displacement of e. m. fs. between transformers....... 610
Angular Velocity. 9
Angular Velocity, Symbol....... 90
Annealed Copper Standard....... 675
Antenna, defined.......1001
Anti-inductive Load....... 25
Apparatus Cable Stranding 655
Apparent Power....... 27
Arc Machines....... 130
Arresters, Lightning.......733, 735
Assurance, Factor of....... 681
Atmospheric Absorption, defined......1002
Attenuation, (Radio) Coefficient of,..1032
Attenuation Constant, defined....... 921
Attenuation, Radio.......1031
Audio Frequencies, defined.......1003
Automobile Apparatus, Test Voltage 505
Automobile Motor and Generator Rating.......835, 836, 837, 838, 839
Auto-Transformer, defined....... 209
Auto Transformer, Voltage Test...... 503
Auxiliary Apparatus, Losses in....... 457
Auxiliary Machine, Expression of Rating....... 277
Available Output....... 261

B

Balancer....... 106
Barometric Pressure for Institute Rating....... 265
Bearing Friction and Windage, determination of....... 450
Bell-Ringing Apparatus, Test Voltage 505
Bibliography on Standardisation, Appendix III
Blower Losses....... 456
Blowout Coils, Temperature Rises.... 731
Booster....... 103
Bracket Systems....... 785
Breakers, Circuit.......724, 728
Bridge Systems....... 786
Brightness, defined....... 861
Brightness, expressed in Lamberts.... 865
Brightness, Normal, defined....... 862
Brown and Sharpe Gage....... 652
Brush Contact Loss 440, 442, 443, 444, 454, ... 819
Brush Friction at Commutator and Collector Rings....... 451, 817
Brush Holders, Temperature of...... 392

SECTION

Brushes, Temperature of 392
By-Laws of Standards Committee .. Page 10

C

Cable, Breakdown Tests of 686
Cable, Concentric, N-Conductor, defined 646
Cable, Concentric-Lay, defined 643
Cable, defined 638
Cable, Duplex, defined 647
Cable, N-Conductor, defined 645
Cable, Rope-Lay, defined 644
Cable Stranding 653, 654, 655, 656, 657
Cable, Triplex, defined 649
Cable, Twin, defined 648
Cables, Capacitance 694, 695, 696, 697, 698, ... 699
Cables, Capacitance of Electric Light and Power 698
Cables, Electrical Tests of 678
Cables, Factor of Assurance 681
Cables, Heating of 677
Cables, Immersion for Testing 679
Cables, Insulation Resistance of 688 to 693
Cables, Insulation Resistance Tests of. 692
Cables, Lengths for Test 678
Cables, Measurement of Capacitance of 696
Cables, Multiple Conductor, Capacity of 699
Cables, Multiple Conductor, Insulation Tests of 693
Cables, Multiple Conductor, Tests of.. 687
Cables, Paired, Capacitance 697
Cables, Safe Limiting Temperature of. 677
Cables, Sectional Area of 654
Cables, Test Voltage 682, 683, 684
Cables, Test Voltage and Frequency 683, 685
Candle, defined 855
Candle Power 856
Capacitance, defined 80
Capacitance, Measurement of 696
Capacitance of Cables .. 694, 695, 696, 697, ... 698, 699
Capacitance, Symbols 90
Capacitive Coupler, defined 1004
Capacity, defined 80, 252, 261
Capacity Distinguished from Rating.. 262
Capacity of Electrical Machines .. 261, 800
Cascade Converter 111
Catenary, Compound 781
Catenary, Simple 781
Catenary Suspension 781
Center Contact Rail 770
Characteristic Curve of Luminous Sources 877
Characteristic Curves of Railway Motors 810, 811, 812
Characteristic Impedance, defined..... 918
Choke Coils, defined 214
Circuit Breakers, definition 724
Circuit Breakers, Performance and Test 726

SECTION

Circuit Breakers, Rating of 725
Circuit, Composited, defined 938
Circuit, Ground Returns, defined 930
Circuit, Metallic, defined 931
Circuit, Phantom, defined 934
Circuit, Simplexed, defined 937
Circuit, Superposed, defined 933
Circuits for Telephony and Telegraphy, definition .... 930 to 938
Circular Inch 652
Classification of Losses in Machinery. 435
Classification of Machinery 100
Classification of Machines for Enclosure 160
Coefficient of Coupling, Inductive 1005
Coefficient of Coupling of a Transformer 962
Coefficient of Reflection 866, 868
Coil Loading 954
Collector Rings and Commutator, Determination of Brush Friction of... 450
Collector Rings, Temperature of 389
Commutating Machines, defined 130, 131, 132
Commutating Machines, A-C., Losses of 443
Commutating Machines, Losses .. 440, 443
Commutation requirements 402
Commutator and Collector Rings, Determination of Brush Friction of. 450
Commutators, Temperature of 390
Comparison, Lamp, defined 874
Compensator, Direct Current 106
Compensator, Line-Drop Voltmeter, defined 230
Components of Current 21, 22
Composited Circuit 938
Concentric-Lay Cable, defined 643
Concentric Strand, defined 642
Condensive Load 25
Conductance, Symbol 90
Conductivity of Copper 675
Conductivity, Symbol 90
Conductor and Rail Systems 766
Conductor, Contact 766
Conductor, defined 636
Conductor, Stranded, defined 637
Conductors, Sizes of 652
Connected Load 61
Connections of Transformers .... 600 to 608
Constant-Current Machines, Regulation of 563
Constant-Potential Machinery, Losses in 433
Constant-Potential Transformer, Rated Current, defined 203
Constant-Speed D-C. Motor, Regulation of 564
Constant-Speed Motors 161
Contact Conductors 766
Contact Rail, Center, defined 770
Contact Rail, defined 767
Contact Rail, Gage 772
Contact Rail, Overhead, defined 768

SECTION
Contact Rail Protection, defined...... 776
Contact Rail, Underground, defined... 771
Contact Voltage Regulators, defined.... 211
Continuous Current, defined.......... 3
Continuous Loading................ 953
Continuous Rating..........281, 287, 288
Continuous Rating, Automobile Motors 835
Continuous Rating, Railway Motors.. 802
Control Apparatus, Dielectric Tests.. 509
Conventional Efficiency, defined...... 423
Converter.......................... 108
Converter, Cascade................ 111
Converter, Direct Current........... 109
Converter, Frequency............... 112
Converter, Regulation, defined....... 566
Converter, Synchronous............. 110
Copper, Conductivity of............ 675
Copper Constant Mass Temperature Coefficient.................... 675
Copper Loss, Railway Motors........ 816
Copper, Temperature Coefficient of... 349
Copper Wire Tables................ 676
Cord, defined...................... 641
Core Loss at No Load......452, 818, 1101
Core Loss, Induction Motors, Determination of.................. 452
Core Loss, Railway Motors, Determination of..................818, 1101
Core Loss, Synchronous Machines, Determination of.............. 452
Core Losses due to Increased Excitation 434
Cores, Temperatures of............. 391
Corrections for Deviation of Ambient Temperature...............320, 321
Correction for Lay................. 656
Counter-clockwise Convention........ 20
Counterpoise, in Radio Telegraphy, defined.......................1007
Coupler (Radio), defined........1016, 1033
Coupling Coefficient................ 962
Crest Voltage Meter................ 227
Crest Factor....................... 15
Critical Resistance, defined..........1014
Cross-Span Systems................ 783
Cross-Span Systems, Messenger....... 784
Current, Alternating, defined.......3, 12
Current, Capacity, defined.......... 80
Current, Continuous, defined......... 4
Current, Direct, defined............ 1
Current, Oscillating, defined......... 5
Current, Pulsating, defined.......... 2
Current Ratio of Transformer........ 206
Current, Symbols................... 90
Current Transformer, defined........ 741
Current Transformer, Tests.......... 500
Cycle............................. 6
Cycle of Duty...................... 284

D

Damped Alternating Current, defined.1008
Damping.....................911, 1008
Damping Constant.................. 912

SECTION
Damping Factor, defined............1009
Decrement, Logarithmic, defined......1018
Decremeter, defined.................1030
Definitions.......................1 to 83
Degree, Electrical, defined........... 7
Degree, Magnetic, defined........... 64
Demand........................... 57
Demand Factor..................... 59
Demand, Maximum................. 58
Demand Meter, defined.....232, 233, 234
Detector, defined...................1010
Dielectric Constant, Symbols......... 90
Dielectric Strength Test Voltage...... ....484, 485, 485a, 486
Dielectric Strength Tests, Condition of Machinery.................... 481
Dielectric Strength Tests, Points of Application of Voltage.......482, 483
Dielectric Tests of Cables........... 680
Dielectric Tests of Circuit Breakers... 727
Dielectric Tests of Machines......... 480
Dielectric Tests of Machines, Voltage Measurements................. 530
Dielectric Tests of Protective Reactors 739
Dielectric Tests of Switches.......... 723
Direct Coupler.....................1006
Direct-Current Commutating Machines 130
Direct-Current Compensator......... 106
Direct-Current Converter........... 109
Direct-Current, defined............. 1
Direct-Current Generators, Expression of Rating..................... 274
Direct-Current Machines, Losses of... 440
Direct Suspension.................. 780
Distortion factor................... 17
Distribution Feeders, Regulation of, defined....................... 567
Distribution System, defined......... 761
Diversity Factor.................... 60
Double-Current Generator.......... 107
Drip-proof Machine................ 168
Drop, Impedance.................. 52
Drop, Per cent.................... 50
Drop, Per cent, in Induction Motors.. 54
Drop, Per cent, in Transformers...... 53
Drop, Reactance................... 51
Drop, Resistance.................. 50
Duplex Cable...................... 647
Duration of Heat Run......322, 323, 324
Duty-Cycle, Equivalent Tests....285, 836
Duty-Cycle Machines, Rating of...... 403
Duty-Cycle Operation............... 284
Dynamotor........................ 105

E

Effective Value.................... 10
Efficiency and Losses............... 420
Efficiency as Affected by Wave-Shape. 431
Efficiency, Alternators and Transformers, defined................. 430
Efficiency, Automobile Motors and Generators.................... 839

SECTION
Efficiency, Conventional, defined 423
Efficiency, defined 83
Efficiency Determination 423, 426
Efficiency, Directly Measured 425
Efficiency, Measurement of 428
Efficiency, Normal Conditions 427
Efficiency, Plant 421
Efficiency, Railway Motors 815 to 820, 1100
Efficiency, Symbol 90
Efficiency, Temperature of Reference .. 432
Electric Locomotives 830
Electric Railways, Standards for 760
Electrical Degree 7
Electro-Magnetic Wave, defined 1011
Electromotive Force, Symbols 90
Electrostatic Field Intensity, Symbol, 90
Electrostatic Flux Density, Symbol ... 90
Electrostatic Flux, Symbol 90
Embedded Temperature Detector Method 352
Enclosed Machine 164
Enclosed Machines, Temperatures 386a
Equivalent Circuit 913, 914, 915
Equivalent Phase Difference 29
Equivalent Sine Wave 18
Equivalent Tests, Standard Duration of 285
Errors of Indicating Instruments, defined 235
Excitation for Regulation Test 583
Explosion-Proof Machine 171
Explosion-Proof Slip-Ring Enclosure .. 172
Exposure 859

F

Factor of Assurance, defined 681
Field-Control Motors, Rating of 806
Field-Rheostat Loss 455
Field Windings of A-C. Generators, Test Voltage 506
Field Windings of Synchronous Machines, Test Voltage 507
Flexible-Cable Stranding 655
Fluctuation, defined 569
Forced Alternating Current 1012
Form Factor, defined 16
Free Alternating Current 1013
Frequencies, Radio 1019
Frequency, defined 9
Frequency Converter 112
Frequency, Group, defined 1015
Frequency of Testing Voltage for Cables 685
Frequency of Testing Voltage for Machines 484
Frequency, Symbol and Abbreviation .. 90
Friction and Windage, Railway Motors 817
Friction, Bearing and Windage Losses, determination of 450
Fuses, definition 729
Fuses, Rating of 730
Fuses, Temperature of 731
Fuses, Test of 732

G SECTION

Gage of Third Rail 772
Gages for Wires 652
Gearing, Losses in 820, 1100
Generator 101
Generator, D-C., Acyclic 144
Generator, D-C., Unipolar 141
Generator, Double Current 107
Generator, Induction, defined 140
Generators, A-C., Regulation of, Tests, Computations 584, 585, 586, 587
Generators, Enclosed, Temperatures of 386a
Generators, Regulation of, defined 561, 562
Globe, defined 894
Graded Insulation for Transformers .. 512
Gravity, Acceleration due to, Symbol and Abbreviation 90
Ground-Return Circuit 930
Group Frequency, defined 1015

H

Heat Run, Duration of 322, 323, 324
Heat Run, Measurements during 325
Heating and Temperature 300
High Temperature Operation, Economy of 301
High-Voltage Winding 202
Horse Power in Terms of Kilowatts ... 276
Hottest Spot Correction 346, 348, 356
Hottest Spot Temperature Table 379
Household Devices, Test Voltage 504
Hydraulic Turbine, Regulation of, defined 570

I

Idle Unit Ambient Temperature 318
I. E. C. Rating 264
Illuminants, Rating and Output ...886, 887
Illumination 854
Illumination and Photometry 850
Illumination, Unit of 858
Immersion of Cables for Testing 679
Impedance, Characteristic 918
Impedance Drop, Per cent 52
Impedance, Mutual 916
Impedance, Self 917
Impedance, Sending-End 919
Impedance, Symbols 90
Incandescent Lamps, Rating of 886
Indeterminable Load Losses 440
Inductance, Symbol 90
Induction Apparatus, Stationary, defined 200
Induction Generator, defined 140
Induction Machines 138
Induction Machines, Losses of 442
Induction Machines, Stray Load Losses of 459
Induction Motor, defined 139
Induction Motor Core Loss, Determination of 452
Induction Motor Rotor Loss 460

SECTION

Induction Motor with Explosion-Proof Slip-Ring Enclosure........ 172
Induction Motors, Drop............ 54
Induction Motors, Phase Wound, Voltage Tests..................... 508
Induction Voltage Regulators, defined. 212
Inductive Coupler, defined...........1016
Inductive Load, defined.............. 25
Inductor Alternator.................. 136
Information on Rating Plate.......... 620
In-Phase Component of Current or Voltage........................ 21
Instrument Transformers............ 741
Instrument Transformers, defined..... 741
Instruments, Dielectric Tests.........510a
Instruments, Indicating, Errors of..... 235
Instruments, Torque of, defined....... 236
Insulation Affected by Temperature... 301
Insulation, Economical Short Life..... 804
Insulation, Life of.................. 340
Insulation Resistance of Cables..688 to 693
Insulation Resistance of Machinery.. 550
Insulation Resistance of Machines Significance.................... 551
Intensity of Illumination............ 853
Intensity of Magnetization, Symbol.. 90
Interconnected Polyphase Windings, Voltage Test.................. 483
Integrated-Demand Meter, defined... 233
Internal Combustion Engines, Regulation of, defined................ 568
I²R Loss, Polyphase Induction Motors 460

K

K, Constant for Cable...........691, 695
Kilovolt-Ampere Rating............. 275
Kilowatt Rating...............274, 276
Kinds of Rating.................... 281

L

Lag.............................. 19
Lagged-Demand Meter, defined....... 234
Lambert, defined.................... 863
Lamp, defined 860
Lamp Accessories................... 892
Lamp, Characteristic Curve, defined.. 877
Lamp, Horizontal Distribution Curve, defined.......................... 878
Lamp, Life Tests................... 890
Lamp, Mean Hemispherical Candle-Power defined................... 882
Lamp, Mean Horizontal Candle-Power, defined......................... 880
Lamp, Mean Spherical Candle-Power, defined......................... 881
Lamp, Mean Zonal Candle-Power, defined............................ 883
Lamp, Performance Curve, defined.... 876
Lamp, Specific Consumption, defined.. 889
Lamp, Specific Output, Expression of.. 888
Lamp, Spherical Reduction Factor, defined 884

SECTION

Lamp, Vertical Distribution Curve, defined.......................... 879
Lamps, Comparison of............... 891
Lay, Correction for.................. 656
Lay of Strands...................... 657
Lead............................. 19
Leads of Transformers, Marking of.. 600
Life of Insulation Affected by Temperature............................ 301
Life of Insulation of a Machine...... 340
Life Tests of Lamps................ 890
Lightning Arresters Definition........ 733
Lightning Arresters, Performance and Test.......................... 735
Lightning Arresters, Rating of....... 734
Limitations, Approved.............. 260
Limitations of Temperature Affecting Capacity....................... 300
Line Characteristics, Telephony and Telegraphy..................... 918
Line Circuits, Telephone and Telegraph ....930 to 939
Line-Drop Voltmeter Compensator.... 230
Linear Capacitance.................. 694
Linear Decrement, defined...........1017
Linear Insulation Resistance.......... 690
Literature on Standardization.......... ....Appendix III.
Load, Anti-Inductive................ 25
Load, Condensive................... 25
Load, Connected.................... 61
Load Factor........................ 55
Load, Inductive..................... 25
Load, Maximum..................... 262
Load, Non-Inductive................ 25
Loaded Line........ 950
Loading of Telephone Lines....950 to 954
Loading Transformers.........393, to 397
Loads, Momentary, Continuously Rated Machines.................. 402
Loads, Momentary, Railway Motors... 803
Loads, Momentary, Railway Substation Machinery.................. 764
Locomotive Speed.................. 834
Locomotives, Continuous Tractive Effort............................ 833
Locomotives, Electric..........830 to 834
Locomotives for Intermittent Service.. 833
Locomotives, Normal Tractive Effort, 832
Locomotives, Rating................ 830
Locomotives, Weight on Drivers...... 831
Logarithmic Decrement, defined..... 1018
Loss Brush-Contact................. 454
Losses, Bearing Friction and Windage, Determination of.............. 450
Losses, Brush Friction, Determination of............................ 451
Losses, Classification of............. 435
Losses, A-C. Commutating Machines, 443
Losses, D-C. Commutating Machines, 440
Losses due to Ventilating Blower...... 456
Losses, Evaluation of................ 436

SECTION

Losses in Auxiliary Apparatus........ 457
Losses in Constant Potential Machinery.......................... 433
Losses in Field Rheostats............. 455
Losses in Railway Motors, . 815 to 820, 1100
Losses in Transformers...........470, 471
Losses, Indeterminable............... 440
Losses, Indeterminate................ 426
Losses, Induction Machines.......... 442
Losses, Stray Load................... 434
Losses, Synchronous Converters,...... 444
Losses, Synchronous Machines........ 441
Losses, Table of,.................... 435
Losses, Transformers................. 445
Low Temperature Operation, Uselessness of,......................... 301
Low-Voltage Winding.................. 202
Lumen............................ 857
Luminous Flux..................850, 857
Luminous Flux, Unit of............... 858
Luminous Intensity.................. 853
Luminous Sources, Comparison of,.... 891
Luminous Standard, Primary......... 870
Luminous Standard, Representative... 871
Luminous Standards...........870 to 873
Lux.............................. 858

M

Machine Classification by Enclosure or Protection...................... 160
Machine Classification by Speed..... 150
Machine, Drip-Proof, defined......... 168
Machine Efficiency..............420, 422
Machine, Enclosed, defined........... 164
Machine, Explosion Proof, defined.... 171
Machine, Moisture Resisting, defined.. 169
Machine, Open, defined.............. 161
Machine Protected, defined.......... 162
Machine Rating, defined............. 262
Machine Rating, Principle of......... 263
Machine, Self-Ventilated, defined..... 167
Machine, Semi-Enclosed, defined...... 163
Machine, Separately Ventilated, defined,.............................. 165
Machine, Submersible, defined........ 170
Machine, Water-Cooled, defined....... 166
Machine with Explosion-Proof Slip-Ring Enclosure, defined.......... 172
Machinery Cooled by Ventilating Air from Distance................... 304
Machinery, defined................. 250
Machinery Exposed to Sun's Rays.... 313
Machinery for High Ambient Temperatures,.......................... 267
Machines, defined.................. 250
Machines, Duty-Cycle Rating of...... 403
Machines not Cooled by Air or Water.. 312
Machines Partly Below Floor Line Ambient Temperature.............. 319
Machines, Synchronous, Determination of Core Loss of................ 452
Magnetic Degree.................... 64

SECTION

Magnetic Field Intensity, Symbols and Abbreviation...................... 90
Magnetic Flux, Symbols,............. 90
Magnetic Flux Density, Symbols,..... 90
Magneto Voltage Regulators, defined, 213
Magnetomotive Force, Symbol....... 90
Marked Ratio of Instrument Transformer,.......................... 207
Mass Resistivity, defined............ 675
Mass, Symbol and Abbreviation....... 90
Maximum Demand.................. 58
Maximum Equipment Line, defined... 768
Maximum Load.................... 262
Mean Hemispherical Candle-Power... 882
Mean Horizontal Candle-Power....... 880
Mean Spherical Candle-Power........ 881
Mean Zonal Candle-Power........... 883
Measurement of Ambient Temperature 314, 315
Mechanical Degree.................. 64
Mechanical Power, Where Measured.. 429
Mechanical Work, Symbol........... 90
Megohms.......................... 689
Megohms Constant................. 691
Messenger Suspension.............. 781
Messenger Wire or Cable........... 778
Metallic Circuits.................... 931
Meter, Demand, defined............. 232
Meter, Power-Factor, defined........ 226
Meter, Reactive-Factor, defined...... 226
Meter, Watthour, defined............ 226
Meters, defined..................... 225
Meters, Dielectric Tests,............510A
Meters, Torque of, defined.......... 236
Microfarads, Constant.............. 695
Microphone, defined................ 955
Millilambert....................... 864
Milliphot.......................... 858
Moisture-Resisting Machine.......... 169
Momentary Loads, Continuously... Rated Machines..................... 402
Momentary Loads, Railway Motors,.. 803
Momentary Loads, Railway Substation Machinery...................... 764
Motor............................ 102
Motor, Automobile Propulsion, Rating,..................835, 836, 837
Motor-Booster..................... 103
Motor-Converter................... 111
Motor-Generator................... 104
Motor, Induction, defined........... 139
Motor, Synchronous, defined........ 137
Motor-Vehicle Ratings... ....835, 836. 837, 838, 839
Motors, A-C., Commutating, Classification.......................... 131
Motors, Adjustable Speed, defined..... 158
Motors, Adjustable Varying Speed, defined........................... 154
Motors, Constant Speed, defined...... 151
Motors, Enclosed, Temperature of....386A
Motors, Expression of Rating,....276, 802

SECTION

Motors, Field Control, Rating of..... 806
Motors, Induction, Determination of Core Loss of.................... 452
Motors, Multispeed, defined.......... 152
Motors, Railway, Characteristic Curve 810, 811, 812
Motors, Railway, Determination of Core Loss of....................
Motors, Railway, Efficiency.......... ....815, to 820, 1100
Motors, Railway, Maximum Input of 803
Motors, Railway, Rating of.....800 to 802
Motors, Railway, Selection of........1102
Motors, Railway, Service Capacity... .... 1103 to 1113
Motors, Railway, Stand-Test Temperature Rises.................... 805
Motors, Speed classification of........ 150
Motors, Speed Regulators............ 564
Motors, Stalling Torque of........... 404
Motors, Varying-Speed, defined....... 154
Multiple-Conductor Cable.......645, 646
Multiple-Conductor Cables, Capacitance.......................... 699
Multiple-Conductor Cables, Tests..... 687
Multi-Speed Motors................... 152
Mutual Impedance.................... 916
Mutual Inductance, Symbol........... 90

N

N-Conductor Cable................... 645
Needle-Point Spark-Over Voltages.... 537
Nominal Rating...................... 283
Nominal Rating, Automobile Motors and Generators.................. 837
Nominal Rating, Railway Motors..... 800
Nominal Rating, Railway Substation Machinery.................... 765
Non-Inductive Load.................. 25
Non-Phantomed Circuit............... 936
Non-Sinusoidal Quantities............ 14
Normal Brightness, defined........... 862
Notation.......................90, 805
Number of Conductors or Turns, Symbol...................... 90

O

Object of Standardization 260
Oil-Cup............................. 316
Oil Temperatures.................... 385
Open Machine........................ 161
Oscillating Current.................. 5
Outdoor Machinery Exposed to Sun's Rays........................ 313
Output, Available.................... 261
Output, Rated, defined.............. 262
Over Speeds..................399 to 401
Overhead Construction.............. 779
Overhead Contact Rail 768

P

SECTION

Pads for Thermometers.............. 317
Pair, Twisted, defined............... 650
Paired Cables....................... 697
Paper Impregnated, Working Temperature......................... 677
Peak Factor......................... 15
Per cent Drop....................... 50
Percentage Saturation............... 63
Performance Curve, Lamp........... 876
Period.............................. 8
Permeability, Symbol................ 90
Phantom Circuit..................... 934
Phantomed Cable.................... 939
Phase............................... 13
Phase Advancer................114, 115
Phase Converter..................... 113
Phase Difference.................... 19
Phase Difference, Equivalent......... 29
Phase Displacement, Symbols........ 90
Phase-Modifier...................... 114
Phase, Single....................... 30
Phase, Six.......................... 33
Phase, Three........................ 31
Phase-Wound Rotors, Dielectric Tests, 508
Phot................................ 858
Photometric Tests................... 885
Photometic Units and Abbreviations 895
Π Equivalent Circuit................ 915
Plant Efficiency, defined............. 421
Plant Factor, defined................ 56
Plate, Rating..................620 to 622
Pole Tips, Temperature of........... 392
Polyphase Alternator, defined........ 135
Polyphase, defined.................. 34
Polyphase Induction Motor, I^2R Loss, 460
Potential Difference, Symbols........ 90
Potential Transformer, defined....... 741
Power Apparent..................... 27
Power Capacity..................... 80
Power-Factor........................ 28
Power-Factor Meter, defined......... 226
Power in A-C. Circuits............... 26
Power, Symbols..................... 90
Primary Luminous Standard......... 870
Primary Winding.................... 202
Prime Movers, Fluctuation of.....65, 569
Prime Movers, Pulsation in.......... 68
Prime Movers, Regulation of......... 568
Prime Movers, Variation in.......... 65
Propagation Constant, defined....... 920
Protected Machine................... 162
Protection of Thermometers.......... 317
Protective Reactors, definition....... 736
Protective Reactors, Performance and Tests............................ 738
Protective Reactors, Rating.......... 737
Publications on Standardization,..... ....Appendix III.
Pulsating Current Defined........... 2
Pulsation........................... 68
Putty for Thermometers............. 317

Q SECTION

Quadded Cable.................... 939
Quadrature Component of Current or Voltage.................... 22
Quantity of Electricity, Symbols...... 90
Quarter-Phase.................... 32

R

Radiation, Sustained, defined.........1029
Radio Communication, Standards for ....1000 to 1033
Radio Frequencies....................1019
Rail, Contact.................... 767
Rail, Third.................... 769
Railway Motor, Selection of...1102 to 1113
Railway Motor, Stand Tests of...815, 1103
Railway Motors..........415, 800 to 820
Railway Motors, Capacity and Requirements of....................1106
Railway Motors, Characteristic Curves of.................... 810
Railway Motors, Continuous Rating of 802
Railway Motors, Determination of Core Loss of..........817, 818, 1101
Railway Motors, Efficiency and Losses of....................815, 1100
Railway Motors, Field Control, Rating of.................... 806
Railway Motors, Friction and Windage 817
Railway Motors, Maximum Input of.. 803
Railway Motors, Temperature Limitations of.................... 804
Railway Motors, Temperature Rise in Service Compared to Stand Test. 1104
Rated Current of Constant-Potential Transformer.................... 203
Rated Output, defined.................... 262
Rating, A. I. E. E.................... 264
Rating, Circuit Breakers.................... 725
Rating, Continuous.................... 281
Rating, Continuous, Automobile Motors.................... 835
Rating, Continuous, Railway Motors 802
Rating Distinguished from Capacity... 262
Rating, Expression of, in Kilovolt-Amperes.................... 275
Rating, Expression of in Kilowatts 274, 276
Rating, Fuses.................... 730
Rating, I. E. C.................... 264
Rating, Locomotives.................... 830
Rating, Nominal.................... 283
Rating of Duty Cycle Machines...... 403
Rating of Electrical Machines, defined 262
Rating of Field Control Railway Motors.................... 806
Rating of Incandescent Lamps........ 886
Rating of Motors, Expression of, in Kilowatts.................... 276
Rating Plate, Information on...620 to 622
Rating, Principle of.................... 263
Rating, Short-Time.................... 282
Rating, Short-Time, Automobile Motors.................... 836

SECTION

Rating, Short Time, Railway Motors. 800
Rating, Switches.................... 722
Ratio, Current, defined.................... 206
Ratio, Marked, defined.................... 207
Ratio of Transformer.................... 204
Ratio, Voltage, defined.................... 205
Ratio, Volt-Ampere, defined.......... 208
Reactance, Coils, defined.................... 214
Reactance Drop, per cent.................... 51
Reactance, Symbols.................... 90
Reactive Component of Current or Voltage.................... 22
Reactive Factor.................... 23
Reactive-Volt-Ammeter.................... 229
Reactive-Volt-Ampere Indicator...... 229
Reactive Volt-Amperes.................... 24
Reactor, defined.............82, 214, 736
Reactor Factor Meter.................... 226
Reactor, Protective...........736 to 739
Receiver, Telephone, defined.......... 960
Recording Instruments.................... 231
Reduction Factor, Spherical.......... 884
Reference Standard.................... 872
Reflection Coefficient.................... 866
Reflection, Coefficient of Diffuse...... 868
Reflection, Coefficient of Regular..... 867
Regulation and Excitation.................... 583
Regulation and Frequency.................... 580
Regulation and Power Factor..... ... 581
Regulation and Wave Form.......... 582
Regulation, Constant-Current Machines 563
Regulation, Constant-Potential Generators.................... 562
Regulation, Constant-Potential Transformers.................... 565
Regulation, Constant-Speed D-C. Machines.................... 564
Regulation, Converters, Dynamotors, Motor-Generators and Frequency Converters.................... 566
Regulation, D-C. Generators.......... 561
Regulation, defined.................... 560
Regulation, Generator Unit.......... 571
Regulation, Hydraulic Turbine...... 570
Regulation of A-C. Generators 584, 585, 586
Regulation, Steam Engines, Turbines, and Internal Combustion Engines 568
Regulation Tests.................... 580
Regulation, Transformers.................... 587
Regulation, Transmission Lines, Feeders, etc.................... 567
Regulators, Voltage, defined.......... ....210, 211, 212, 213
Relay, defined.................... 956
Reluctance, Symbol.................... 90
Repeating Coil.................... 963
Representative Luminous Standard, defined.................... 871
Resistance Drop, per cent.................... 50
Resistance, Insulation, of Machines.. 550
Resistance Method of Measuring Temperature....................348, 350

SECTION
Resistance, Symbols.................. 90
Resistivity, Symbol and Abbreviation 90
Resistor..........................81, 740
Resonance.....................957, 1020
Resonance Curve.....................1024
Retardation Coil..................... 958
Revisions to Rules, Scope of........Page 3
Rheostat, definition................. 740
Rheostat, Field, Losses.............. 455
Root-Mean-Square..................... 10
Rope-Lay Cable....................... 644
Rotary Phase-Converter............... 113
Rotating Machines, Classification by Function........................ 101
Rotating Machines, Forced Draft, Ambient Temperature........... 311
Rubber Insulation, Maximum Working Temperature.................... 677
Rupturing Test, Circuit Breakers...... 728

S

Saturation Factor.................... 62
Saturation, Percentage............... 63
Secondary Winding.................... 202
Self-Impedance....................... 915
Self-Ventilated Machine.............. 167
Semi-Enclosed Machine................ 163
Sending-End Impedance, defined...... 919
Separately Ventilated Machines....... 165
Series Field Coils, Dielectric Tests... 507
Series Loaded Line................... 951
Series Transformers.................. 741
Shade, defined....................... 893
Short-Circuit Stresses............... 398
Short Time Rating.................... 282
Short Time Ratings, Standard Periods 285
Short Time Tests, Conditions for..... 286
Shunt-Loaded Line.................... 952
Side Circuit......................... 935
Simple Alternating Current........... 12
Simplexed Circuit.................... 937
Sine Wave............................ 11
Sine Wave, as Standard............... 405
Sine Wave, Deviation from............ 406
Single-Phase......................... 30
Sinusoidal Current................... 12
Six-Phase............................ 33
Skin Effect.......................... 959
Slip Rings, Temperatures of.......... 389
Spark-Frequency.....................1015
Spark Gap for Machinery of High Capacitance...................... 532
Spark Gap for Machinery of Low Capacitance...................... 531
Spark Gap Measurements........530, 534
Spark Gap, Needle.................... 536
Spark Gap, Range of Voltage.......... 535
Spark Gap, Sphere.................... 538
Sparking Distance, Needle............ 537
Sparking Distance, Sphere Gap........ 540
Special Temperature Limits........... 385
Specific Consumption................. 889

SECTION
Specific Luminous Radiation.......... 860
Specific Output of Lamps............. 888
Speed Classification of Motors....... 150
Speed Regulation of Machines......... 560
Speeds, Above Rated.......399, 400, 401
Sphere Gaps, Conditions for Test.... 539A
Sphere Gap, Correction Factor for Air Density.......................... 541
Sphere Spark Gap..................... 538
Spherical Reduction Factor........... 884
Spherometer.......................... 539
Squirrel Cage Windings, Temperature of................................ 388
Stalling Torque of Motors............ 404
Stand Test Temperatures, Railway Motors........................... 805
Standard Duration of Equivalent Tests 285
Standard Resonance Curve............1024
Standard Temperature for Institute Rating........................... 265
Standard, Working (Photometric)..... 873
Standardisation, Objects of.......... 260
Standards for Electrical Machinery... 250
Standards for Telegraphy and Telephony.......................910 to 963
Stationary Induction Apparatus, defined............................ 200
Steam Engines, Regulation of, defined 568
Steam Turbines, Regulation of, defined, 568
Stimulus Coefficient.........851, 852
Strand, Concentric, defined.......... 642
Strand, defined...................... 639
Stranded Conductor, defined.......... 637
Stranded Wire, defined............... 640
Stranding, Apparatus Cable,.......... 655
Stranding, Bunched................... 655
Stranding, Flexible.................. 655
Stranding, Rope...................... 655
Stranding, Rope-Lay, Symbol for,..... 655
Stranding, Standard.................. 653
Stray Load Losses, defined........... 434
Stray Load-Losses, Determination of 458, 459
Submersible Machine.................. 170
Substation, definition............... 762
Substation Machinery Rating.......... 763
Superposed Circuit................... 933
Supporting Systems for Trolley Wires, 782
Susceptance, Symbol.................. 90
Susceptibility, Symbol............... 90
Suspension, Direct, for Trolley...... 780
Sustained Radiation, defined........1026
Switches, definition................. 721
Switches, Dielectric Tests,.......... 509
Switches, Performance and Tests of... 723
Switches, Rating of.................. 722
Symbols.............................. 90
Symbols, Photometric................. 895
Synchronism Indicator, defined....... 228
Synchronoscope, defined.............. 228
Synchronous Commutating Machines 132
Synchronous Condenser............... 115

SECTION

Synchronous Converter, defined....... 110
Synchronous Converters, Losses of.... 444
Synchronous Machine Core Loss, Determination of.................. 452
Synchronous Machines............... 133
Synchronous Machines, Losses of..... 441
Synchronous Machines, Stray Load Losses,.......................... 458
Synchronous Motor, defined......... 137
Synchronous Phase-Advancer......... 115
System Efficiency, defined............ 421

T

T Equivalent Circuit................ 914
Tables of Copper Wire............... 676
Telephone Receiver.................. 960
Telephone Transmitter............... 961
Telephony and Telegraphy.......910 to 963
Temperature, Ambient............... 303
Temperature, Ambient, for Testing... 307
Temperature, Ambient, Forced Draft Machines......................... 311
Temperature, Ambient, from Idle Unit, 318
Temperature, Ambient, Measurement of..........................314, 315
Temperature and Life of Insulations.. 301
Temperature Coefficient of Copper.... 349
Temperature Correction for Air-Blast Transformers.................. 321
Temperature Detectors...........353, 354
Temperature Elevations, Table of..... 379
Temperature, High, Conditions for Operation at,..................... 301
Temperature Limitations and Capacity.........................300, 804
Temperature Limits.................. 375
Temperature Limits, Enclosed Machines,.........................386A
Temperature Limits for Low Ambients...........................305A
Temperature, Maximum, Derived from Observable,.................... 343
Temperature Measurements.......... 344
Temperature Measurements during Heat Run 325
Temperature Measurements, Imbedded Detector Method...353, 354, 355, 356
Temperature Measurements, Resistance Method...............348, 350
Temperature Measurements, Thermometer Method............345, 346, 347
Temperature of Parts Other than Windings.........388, 389, 390, 391, 392
Temperature of Reference for Air..... 305
Temperature of Reference for Efficiency,.......................... 432
Temperature of Reference for Water... 309
Temperature of Transformer Winding. 351
Temperature Rise in Coils for Fuse Blowouts........................ 731
Temperature Rise Limits for Low Ambients.........................305A

SECTION

Temperature Rise, Switches.......... 722
Temperature Rises with Ambient Less than Standard.................. 266
Temperature Scale.................. 251
Temperature, Standard.............. 265
Temperature, Symbols and Abbreviation,......................... 90
Temperature Test, Duration of.......
.......................322, 323, 324
Temperature Tests of Transformers...
..................393, 394, 395, 396, 397
Temperatures and Temperature Rises Permissible..............376, 377, 379
Temperatures Desirable to Ascertain.. 341
Temperatures, Hottest Spot, Table of, 379
Temperatures in Centigrade.......... 251
Temperatures, Limiting, Observable.. 379
Temperatures, Low, Uselessness of.... 301
Temperatures of Oil................. 385
Temperatures, Permissible, in Mixed Insulations...................... 378
Temperatures, Safe, for Operating Railway Motors.................... 804
Test Lamp, defined.................. 875
Test Voltage for Cables.............. 682
Test Voltage, Measurement of.....530, 540
Test Voltages, Conditions for......... 481
Test Voltages, Duration of........... 485
Test Voltages for Machines.......... 480
Test Voltages, Frequency and Wave Form,.......................... 484
Test Voltages, Values of and Exceptions,.....................500, 512
Testing of Cables, Immersion in Water, 679
Thermal Capacity, defined............1111
Thermometer Method of Measuring Temperature......345, 346, and 347
Thermometer Pads and Putty........ 317
Third Rail......................... 769
Third Rail, Elevation of............. 773
Third Rail, Gage of................. 772
Third Rail, Protection............... 776
Third Rail, Standard Elevation of..... 775
Third Rail, Standard Gage of......... 774
Three-Phase..........................31
Three-Phase Transformers, Marking Leads of,........................ 607
Time Lag, Error due to,............. 316
Time, Symbol and Abbreviation...... 90
Torque of Meters and Instruments.... 236
Torque, Stalling, of Motors.......... 404
Tractive Effort.................832, 833
Tractive Effort, Locomotives,.....832, 833
Transformer, Coefficient of Coupling.. 962
Transformer Connections............ 600
Transformer, Constant-Potential, Rated Current, defined............ 203
Transformer, Constant-Potential, Rated Primary Voltage, defined..... 203
Transformer, Current Ratio, defined... 206
Transformer, High-Voltage Winding, defined,........................ 202

SECTION
Transformer, Instrument, defined..... 741
Transformer, Low-Voltage Winding, defined........ 202
Transformer, Marked Ratio, defined... 207
Transformer, Primary Winding, defined 202
Transformer, Ratio of..........204, 207
Transformer Regulation......587, 588, 589
Transformer Regulation, defined...... 565
Transformer, Secondary Winding, defined........ 202
Transformer Testing by Induced Voltage........ 511
Transformer, Three-Phase, Method of Loading........ 395
Transformer, Turn Ratio, defined.... 204
Transformer, Voltage Ratio, defined... 205
Transformer, Volt-Ampere Ratio, defined........ 208
Transformer Windings, defined....... 201
Transformer Windings, Grounded, Voltage Tests........ 512
Transformers........ 201
Transformers, Angular Displacement... 610
Transformers, Angular Displacement between........ 608
Transformers, Constant-Potential, Regulation of........ 565
Transformers, Distributing Test Voltages........ 502
Transformers, Expression of Rating... 275
Transformers, Load Losses........ 471
Transformers, Loading-Back Tests.... 394
Transformers, Loading for Temperature Tests........ 393
Transformers, Losses of........ 445
Transformers, Marking of Leads 601 to 611
Transformers, No-Load Losses........ 470
Transformers, per cent Drop........ 53
Transformers, Reactance Drop....... 587
Transformers, Regulation of........ 587
Transformers, Stray Load Losses...... 471
Transformers, Temperature Measurements of........ 351
Transformers, Volt-Ampere Ratio..... 208
Transformers, Water-Cooled, Ambient Temperature..........309, 310
Transformers, Water-Cooled, Temperature........ 386
Transformers with Graded Insulation 512
Transmission Lines, Regulation of, defined........ 567
Transmission System, defined........ 760
Transmitter, Telephone, defined...... 961
Triplex Cable........ 649
Trolley, Classes of Suspension........ 779
Trolley, Direct Suspension, defined.... 780
Trolley, Messenger or Catenary Suspension........ 781
Trolley over Steam Railroad Tracks.. 787
Trolley Supporting Systems....782 to 786
Trolley Wire, defined........ 777
Trolley Wire Height, Standard........ 787

SECTION
Tuning, defined........1027
Turbine, Hydraulic, Regulation of... 570
Turbine, Steam, Regulation of........ 568
Twin Cable, defined........ 648
Twin Wire, defined........ 651
Twisted Pair, defined........ 650
Two-Phase........ 32
Two-Wire Circuit........ 932

U

U Equivalent Circuit........ 915
Underground Contact Rail........ 771
Unipolar Machine, defined........ 141
Unit, Generator, Regulation of, defined 571
Units in which Rating shall be Expressed..........274 to 277
Units, Photometric........ 895

V

Variation in Prime Movers and Alternators..........65, 66, 67
Varnished Cambric Insulation, Working Temperature........ 677
Varying-Speed Motors........ 154
Vector Diagram........ 20
Vector, Phase........ 13
Vector Quantities, Representation in Print........ 91
Velocity of Rotation, Symbol and Abbreviation........ 90
Ventilated Motor, Rise Compared to Stand Test........1104
Ventilating Blower Losses........ 456
Virtual........ 10
Voltage Measurement for Dielectric Tests..........530 to 541
Voltage Measurement in Dielectric Tests of Machines........ 530
Voltage Ratio of Transformer, defined 205
Voltage Regulation........ 560
Voltage Regulators, defined........ ....210, 211, 212, 213
Voltage, Symbols........ 90
Voltage Tests, Conditions for........ 481
Voltage Tests for Machines.....480 to 512
Voltage Transformer, defined........ 741
Voltage Transformer, Tests........ 500
Volt-Amperes........ 27
Voltmeter Measurements........ 533
Volume Resistivity, defined........ 675

W

Water-Cooled Machine........ 166
Water-Cooled Machines, Ambient Temperature of Reference........ 309
Water-Cooled Transformers........ 310
Water-Cooled Transformers, Temperature of........ 386
Watt-Hour Meter, defined........ 226
Wattmeter........ 231
Wave, Crest-Factor........ 15

SECTION
Wave, Distortion Factor.............. 17
Wave, Electromagnetic, defined.......1011
Wave, Equivalent-Sine................ 18
Wave Form.......................11, 405
Wave-Form Deviation.................. 406
Wave, Form Factor.................... 16
Wave-Length Constant, defined........ 922
Wave-Length Meter....................1028
Wave-Meter...........................1028
Wave Shape........................... 11
Wave Shape and Efficiency............ 431
Wave, Sine, as Standard.............. 405
Wave, Sine, Deviation from........... 406
Weatherproof Cable Stranding......... 653

SECTION
Weight on Drivers.................... 831
Windage and Bearing Friction
Losses, Determination of............. 450
Windage, Railway Motors.............. 817
Wire, Copper, Tables of.............. 676
Wire, defined........................ 635
Wire Gages........................... 652
Wire, Half Sizes..................... 655
Wire or Cable, Messenger............. 778
Wire, Stranded, defined.............. 640
Wire, Trolley, defined............... 777
Wire, Twin, defined.................. 651
Wires and Cables..................... 635
Working Standard, Illumination....... 873

REPORT OF THE JOINT RUBBER INSULATION COMMITTEE—1916

PART I—GENERAL REPORT

Need of Specifications

1. A demand for specifications which will enable purchasers of rubber insulation for wire or cable to secure good material on the basis of competitive bids has existed for many years.

2. In recent years, there has been no difficulty in securing insulation having the dielectric strength, specific resistance, elasticity and mechanical strength required in practise. Indeed, with the possible exception of dielectric strength, these qualities are usually in excess of actual service requirements. There is another quality, namely, permanence, which although equally essential, has not been so easy to obtain.

3. While the physical properties of rubber insulation are susceptible of positive determination by tests which can be made before acceptance by the purchaser, the permanence of insulation can be ascertained with certainty only by actual trial, often at great loss, inconvenience and even danger. It should, therefore, be the aim of specifications to overcome this difficulty and by some indirect means, ensure that the manufacturers supply compounds having the required endurance.

4. This obviously presents a difficult problem, as it requires that some relation be established between permanence and one or more of the properties which are susceptible of test. It has been established by experience that Hevea rubber or the rubber of the Hevea Brasiliensis tree, when properly cured, is a superior grade which is entirely satisfactory for electrical insulation of the class under consideration. Hevea rubber may, therefore, be specified with advantage, although certain other rubbers of good quality may thereby be excluded. The rubber has to be Hevea rubber of good quality, the materials associated with it in the compound must be known to be non-deleterious and the compound itself must be well prepared, applied and vulcanized.

Types of Specifications

5. Two types of specifications have been devised to compass these restrictions. The first type of specification proceeds on the assumption that certain physical characteristics are developed to an unusual degree by the use of Hevea rubber, especially the grade known as fine Para. Among the qualities affected by the grade of rubber, and alleged to be useful indications of the presence of Para rubber, are the tensile strength, elasticity and specific electrical resistance. Accordingly some specifications have been issued in which one or more of these qualities is specified

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This report has been approved by the Standards Committee, and is published by order of Board of Directors.

in an exaggerated degree. Experience has shown that such specifications are ineffective, as the specified physical quality can be obtained either by manipulation of poor compounds or at the expense of permanence in compounds made originally of good materials. In consequence of this, specifications based exclusively on physical tests have fallen into disrepute, but such tests now serve in modified form as adjuncts to other types of specifications.

6. The second type of specification to be considered is that in which a more or less rigid formula for the compound is specified and compliance with it exacted either by inspection during manufacture, or by chemical analysis supplemented by other tests of the finished product. Inspection which will really ensure compliance with such specifications is usually impracticable. Reliance must, therefore, be placed principally upon chemical analysis. Three difficulties at once arise. In the first place chemical analysis cannot directly ascertain the quality of the rubber which has been used in the manufacture of a compound; it can only determine quality by the indirect method of measuring certain characteristic constituents. It is, therefore, necessary to present in the specification, a relation between the desired formula and the chemical findings. The second difficulty is that in the past, chemists have employed diverse methods of analysis which give inconsistent results. It is, therefore, necessary to establish a satisfactory and standard procedure for analysis. The method of analysis must not only yield the information desired, but it must also be practical and capable of yielding uniform results when applied to the same compound by different chemists. In order to secure this uniformity, it is important to describe the methods of analysis in detail. The third difficulty has been the non-uniform interpretation of analytical results.

7. The specification hereinafter presented is of the second or chemical type, in which an endeavor has been made to meet the three objections hitherto urged against such specifications. It contains a table showing the range of analytical results that should be obtained from a good compound containing 30 per cent of high class Hevea rubber, and is supplemented by a detailed analytical procedure. The specification is not complete as given, it being necessary to add appropriate electrical and mechanical test requirements. Examples of complete rubber insulation specifications are cited in Part VI. of this report.

8. The specification should always be used in conjunction with the analytical procedure. The latter will, however, serve for the analysis of any compounds of the 30 per cent Para type with mineral fillers, provided the interpretation is made to correspond.

History of Committee

9. The necessity of purchasing insulated wire under conditions of competitive bidding led the various departments of the government, the railroads and other large consumers, to issue specifications for rubber insulation. These specifications were based upon the individual experience or theories of a number of engineers, aided by suggestions from some of the manufacturers. For several years no attempt was made to standardize these specifications, and much trouble was given to the manufacturers by

the diversity of requirements contained in them. In 1906, the Rubber-Covered-Wire Engineers' Association, consisting of representatives of the leading manufacturers, prepared a specification which was offered as a standard. This was followed in 1911 by the revised specifications of the National Board of Fire Underwriters, which, however, call for a comparatively low grade of compound. The former specification, although the best that could be agreed upon at that date, was so defective as to afford little or no protection to consumers. The latter occupies a field by itself, and makes no pretension to specifying the highest quality of compound. Consumers desiring high grade insulation of great permanence, therefore, continued to use their own specifications, altering them from time to time, in accordance with the best information available, with a growing tendency to rely upon chemical rather than physical tests. Some difficulty was experienced both in obtaining bids and in enforcing these specifications owing to the inability of chemists to make concordant analyses of rubber compounds. This matter reached an acute stage in 1911, when a number of manufacturers and consumers held a conference in order to discuss the possibility of standardizing specifications and analytical methods for rubber insulation. This conference was held at New York on the seventh of December, 1911, Col. Samuel Reber of the U. S. Signal Corps presiding.* The following interests were represented:

Signal Corps, U. S. Army,
American Chemical Society,
Lederle Laboratories,
New York Central Lines,
Pennsylvania R. R. Co.,
General Electric Co.,
Hazard Manufacturing Co.,
Simplex Wire & Cable Co.,
Standard Underground Cable Co.

10. After a full discussion of the subject, a committee was appointed to devise a specification and an analytical procedure for rubber insulation, the committee to report at a future conference. The chairman, assisted by other members, appointed the following to serve upon this committee which was named "The Joint Rubber Insulation Committee."

C. R. Boggs, Simplex Wire & Cable Co.,
W. S. Clark, General Electric Company,
W. A. Del Mar, N. Y. C. R. R. Co., (later Interborough Rapid Transit Co.)
W. B. Geiser, N. Y. C. R. R. Co.,
J. P. Millwood, Consulting Chemist,
P. Poetschke, Lederle Laboratories,
H. B. Rodman, Pennsylvania R. R. Co.

Later, at the request of the committee and by unanimous consent of the members of the original conference, the following were added:

J. B. Tuttle, U. S. Bureau of Standards,
E. L. Willson, Hazard Manufacturing Company.

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* The invitations were issued by Mr. E. B. Katte, Chief Engineer of Electric Traction, of the New York Central R. R. Co.

11. W. A. Del Mar was elected secretary of both the Conference Committee and of the Joint Rubber Insulation Committee. No permanent chairman was elected, it being left to the committee to elect a chairman at each meeting.

12. The committee immediately upon its formation decided to confine itself to the development of a specification and an analytical procedure for compounds of the 30 per cent Para type. In accordance with this policy it made a study of the chemical characteristics of Hevea rubber and of the available analytical procedures. New procedures were also developed and studied. Samples of different rubber compounds were analyzed by these tentative methods. The results were unsatisfactory and the discrepancies were investigated. Sub-committees were formed to do much of this work. Twelve regular committee meetings, besides numerous sub-committee meetings, were held; many different compounds were distributed to be analyzed by the entire committee, and others were experimented upon by the sub-committees and individual members.

13. After two years of this work the committee presented a preliminary report to a second conference which was held at New York on October 15th, 1913, Col. Reber again presiding. The report was unanimously accepted by the conference and the committee authorized to continue in existence for another year for the purpose of making any revisions that might appear necessary in its report, as the result of a year of experience with it.

14. The committee was also authorized to publish the preliminary report. This was accomplished through the courtesy of the American Chemical Society, the American Institute of Electrical Engineers, and the U. S. Bureau of Standards; the report appearing in their official publications, the Journal of Industrial and Engineering Chemistry, (January 1914), the Proceedings of the American Institute of Electrical Engineers, (January 1914), and Bureau of Standards Circular No. 38, respectively.

15. Instead of reporting in a year, the committee found it necessary to devote nearly three years to this work, holding 13 additional meetings, or a total of 25 general meetings exclusive of sub-committee meetings.

16. The committee was authorized, at the second conference, to increase its personnel without securing the approval of the Conference Committee. It has added the following chemists to its membership:

A. E. Ellis, Interborough Rapid Transit Co., New York,
G. d'Eustachio, Standard Underground Cable Co.,
E. W. Gundy, Pennsylvania R. R. Co.,
C. W. Walker, American Steel & Wire Co.,
C. F. Woods, A. D. Little Co., Inc., Boston.

17. The following resignations have been accepted since the second conference:

J. P. Millwood,
P. Poetschke.

Mr. Geiser also resigned, due to stress of other work, but has been reelected.

18. The Joint Rubber Insulation Committee's specification for rubber insulating compound has been adopted by the principal engineering so-

cieties which issue standards of the kind. Among these are the American Electric Railway (Engineering) Association, the Association of Railway Electrical Engineers and the American Society for Testing Materials. The specification has also been adopted by a large number of important purchasers of insulated wire, including The U. S. Signal Corps, the Panama Canal, the New York Central R. R. Co., the Interborough Rapid Transit Co., the Public Service Corporation of New Jersey, etc.

19 The committee also desires to express its thanks to the many gentlemen not members, who have actively participated in the work, especially to Messrs. F. S. Deemer, F. A. Hull, M. M. Kahn, C. B. Martin, G. H. Savage, J. F. Tinsley and D. Whipple.

Part II—Specification for 30 Per Cent Hevea Rubber Compound (Chemical Clauses)

1. A 30 per cent fine Para or best quality plantation Hevea rubber compound with mineral fillers, shall be furnished. It shall contain only the following ingredients:

Rubber,
Sulphur,
Inorganic mineral matter,
Refined solid paraffine or ceresine.

2. The vulcanized compound shall conform to the following requirements, when tested by the procedure of the Joint Rubber Insulation Committee, results being expressed as percentages by weight of the whole sample:

Requirements Independent of the Amount of Rubber Found

	Maximum	Minimum
Rubber	33	30
Waxy hydrocarbons	4	..
Free sulphur	0.7	..

Red lead, carbon, or organic fillers shall not be present.

Requirements Dependent Upon Amount of Rubber Found.

(Requirements for intermediate percentages shall be in proportion to the percentage of rubber found).

Limits allowed for 30 per cent Rubber Compound.	Maximum	Minimum
Saponifiable acetone extract	1.35	0.55
Unsaponifiable resins	0.45	....
Chloroform extract	0.90	....
Alcoholic potash extract	0.55	....
Total sulphur (see note 2)	2.10	....
Specific gravity	....	1.75
Limits allowed for 33 per cent Rubber Compound.		
Saponifiable acetone extract	1.50	0.60
Unsaponifiable resins	0.50	....
Chloroform extract	1.00	....
Alcoholic potash extract	0.60	....
Total sulphur (see note 2)	2.30	....
Specific gravity	....	1.67

3. The acetone solution shall not fluoresce.

4. The acetone extract (60 cu. cm.) shall be not darker than a light straw color.

5. Hydrocarbons shall be solid, waxy and not darker than a light brown.

6. Chloroform extract (60 cu. cm.) shall be not darker than a straw color.

7. Failure to meet any requirement of this specification will be considered sufficient cause for rejection.

8. Contamination of the compound, such as by the use of impregnated tapes, will not excuse the manufacturer from conforming to this specification.

Note: 1—This specification shall be supplemented by appropriate clauses relating to tensile strength, elasticity, electric insulation resistance and dielectric strength. (See the Wire and Cable specifications of the American Society for Testing Materials, the Association of Railway Electrical Engineers etc., for examples of such clauses.)

Note 2:—The limit on total sulphur may be omitted at the option of the purchaser. See Part IV, of Report.

PART III—ANALYTICAL PROCEDURE

Object of the Analysis

1. The object of this procedure of analysis is to determine whether rubber compounds comply chemically with the accompanying specification which is intended to secure compounds containing 30 per cent of the best Hevea rubber, and mineral fillers.

Outline of Procedure

2. The general procedure is shown by the accompanying Diagram A.

General

3. Make the analysis upon the insulation after vulcanization and, whenever possible, before the saturation of the braid. Wipe the insulation thoroughly with a damp cloth to remove any adhering material, but do not remove waxy hydrocarbons from the surface.

4. If, however, a saturated braided sample must be used, remove the braid and sandpaper the insulation to a depth of at least 0.005 of an inch and wipe with a damp cloth. The latter procedure, however, is not to be recommended, as it may cause an appreciable error in the acetone extract. In such cases report the condition of the sample.

5. Perform all determinations in duplicate and take the average value arbitrarily as the true value. Duplicate determinations must check within the limits specified.

6. Make blanks on all determinations and deduct the results accordingly.

Sample

7. Remove the insulation entirely from sufficient wire to give a sample weighing about 25 grams. Cut this into small pieces* and grind slowly in either a No. 0 Enterprise coffee mill or a mill such as shown by the accompanying Diagram B. Adjust the grinder so that not more than 20 per cent will pass through a 40-mesh sieve. Sift all the material through a

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* This is most conveniently done with a meat-chopper,

20-mesh sieve, regrinding what is retained on the sieve until the entire sample has passed through. The wires of the sieves shall be evenly spaced in both directions and shall be of 0.016 and 0.010 inches diameter in the 20-mesh and 40-mesh sieves respectively. Remove with a strong magnet any metal that may have come from the grinder and thoroughly mix the sample.

Extraction Apparatus

8. The extraction apparatus shall conform with the accompanying Diagram C. It shall be heated so that the period of filling an empty syphon cup with acetone and completely emptying it, will be between two and one-half and three and one-half minutes.

Preparation of Reagents

9. Acetone shall be freshly distilled over anhydrous potassium carbonate using the fraction 56-57 deg. cent.

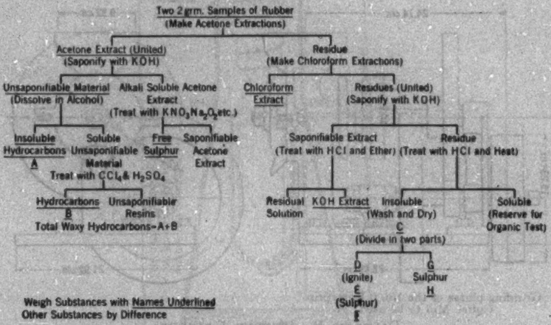

Two 2 grm. Samples of Rubber
(Make Acetone Extractions)
Acetone Extract (United)
(Saponify with KOH)
Residue
(Make Chloroform Extractions)
Unsaponifiable Material
(Dissolve in Alcohol)
Alkali Soluble Acetone Extract
(Treat with KNO3Na2O2etc.)
Chloroform Extract
Residues (United)
(Saponify with KOH)
Insoluble Hydrocarbons
A
Soluble Unsaponifiable Material
Free Sulphur
Saponifiable Acetone Extract
Saponifiable Extract
(Treat with HCl and Ether)
Residue
(Treat with HCl and Heat)
Treat with CCl4 & H2SO4
Hydrocarbons
B
Unsaponifiable Resins
Total Waxy Hydrocarbons=A+B
Residual Solution
KOH Extract
Insoluble
(Wash and Dry)
C
(Divide in two parts)
Soluble
(Reserve for Organic Test)
D
(Ignite)
E
(Sulphur)
F
G
Sulphur
H
Weigh Substances with Names Underlined
Other Substances by Difference

Diagram A—Outline of Method of Rubber Analysis Exclusive of Total Sulphur Determination

10. Alcoholic potash solution shall be of normal strength and shall be made freshly by dissolving the proper amount of potassium hydrate (purified by alcohol), in 95 per cent alcohol which has previously been distilled over potassium hydrate. The solution shall be allowed to stand for 24 hours and only the clear liquid used.

11. Ether shall be washed with three successive portions of distilled water and distilled, using the fraction 34-36 deg. cent.

12. Chloroform shall be shaken with water, dried by calcium chloride, decanted, and freshly distilled, only the clear distillate being used.

13. Carbon tetrachloride shall be pure and freshly distilled.

14. The nitric acid bromine reagent shall be prepared by adding a considerable excess of bromine to the concentrated nitric acid shaking thoroughly and allowing it to stand for some hours before using.

15. The fusion mixture for sulphur determinations shall be made by

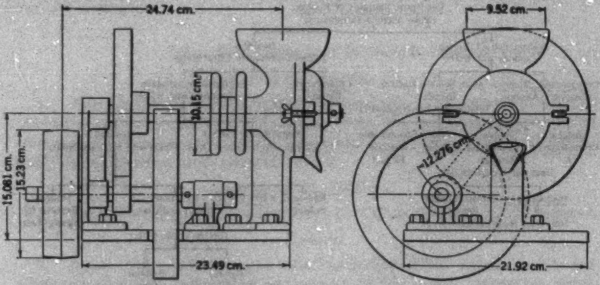
mixing equal quantities of sodium carbonate and powdered potassium nitrate.

16. The barium chloride solution shall be made by dissolving 100g. of crystallized barium chloride in one liter of distilled water and adding two or three drops of concentrated hydrochloric acid. If there is any insoluble matter or cloudiness, the solution shall be heated on a steam bath overnight and filtered through 589 S. and S. blue ribbon filter paper.

17. Distilled water only shall be used in preparing solutions and in all washing operations. Reagents not otherwise specified shall be of a "c.p. tested" quality.

Acetone Extract

18. Extract continuously with 60 cu. cm. acetone for eight hours, two 2-g. samples that have been prepared within 24 hours. Unite the extracts in a weighed flask, using hot chloroform to rinse the flasks. Distill off the reagents and dry the flask and contents for four hours at 95-100 deg. cent. Desiccate until cool and weigh. Continue to dry for two-hour periods until constant weight is obtained. In drying, place the flask on its side but at a sufficient angle from the horizontal so that the extract does not appreciably run down the side of the flask.



Grinding plates of the No. 0 Enterprise Coffee Mill to be used

DIAGRAM B—RUBBER GRINDER

Unsaponifiable Material

19. Add to the acetone extract 50 cu. cm. alcoholic potash solution, boil under a reflux condenser for two hours, and evaporate on a water bath until all alcohol is removed. Add 10 cu. cm. water and 20 cu. cm. ether; heat until the wax etc. are in solution, cool, transfer to a separatory funnel, wash out the flask with warm water, cool and finally wash with two 20 cu. cm. portions of ether. The water volume should be 100 cu. cm. and the ether at least 40 cu. cm. Shake vigorously for two minutes, and allow the solutions to separate thoroughly. Draw off the aqueous solution into a second funnel, leaving in the first funnel the ethereal solution and any flocculent material that may be present. Again rinse the flask

with 20 cu. cm. ether and add it to the aqueous solution; shake vigorously for two minutes, and when separated draw off the aqueous solution and unite in the first funnel the ethereal solutions and any flocculent material. Repeat, shaking with 20 cu. cm. portions of ether, until no residue is obtained on evaporating a 20 cu. cm. portion. The aqueous solution and subsequent washings shall be reserved for the free sulphur determination. Wash the flask and the funnel, from which the ethereal solution has been taken, with water, until they are free from alkali. Wash the ethereal solution with water until it has been washed twice after the wash water shows no alkaline reaction. Retain with the ethereal solution any flocculent material. Filter the ethereal solution from the flocculent material, through a small pellet of extracted cotton, into a weighed flask, washing first with ether and subsequently with hot chloroform, using this to rinse the original flask and both separatory funnels. Evaporate the solvents and dry the extract at 95-100 deg. cent.; cool in a desiccator and weigh. Continue to dry until constant weight is obtained.

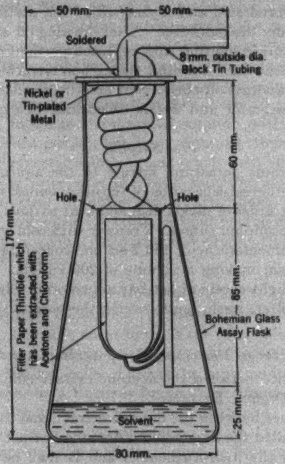

50 mm.
50 mm.
Soldered
8 mm. outside dia. Block Tin Tubing
Nickel or Tin-plated Metal
60 mm.
Hole
Hole
170 mm.
85 mm.
Filter Paper Thimble which has been extracted with Acetone and Chloroform
Bohemian Glass Assay Flask
25 mm.
Solvent
80 mm.

DIAGRAM C—RUBBER ANALYSIS EXTRACTION APPARATUS

Hydrocarbons A

20. Add 50 cu. cm. absolute alcohol to the unsaponifiable material and warm until solution is as complete as possible. Cool the solution to −4 or −5 deg. cent. and maintain at this temperature for one hour by packing the flask in a mixture of ice and salt. Filter out the waxy hydrocarbons, using a funnel packed with ice and salt, and apply suction if necessary. Wash the flask and filter with about 25 cu. cm. of 95 per cent alcohol,

which has been previously cooled in the same temperature. Catch the filtrate in a flask which is afterwards cooled to -4 to -5 deg. cent. to make sure that all possible waxy hydrocarbons have been removed, and refilter if necessary. Dissolve the residue on the filter paper with hot chloroform, into the original flask. Evaporate the chloroform and dry the flask at 95-100 deg. cent.; cool in a desiccator and weigh. Continue to dry until constant weight is obtained.

Hydrocarbons B

21. Evaporate the alcohol from the flask containing the alcohol-soluble unsaponifiable material, add 25 cu. cm. of carbon tetrachloride, and transfer to a separatory funnel. Shake with concentrated sulphuric acid, drain off the discolored acid and repeat with fresh portions of acid until there is no longer any discoloration. After drawing off all the acid, wash the carbon tetrachloride solution with repeated portions of water until all traces of acid are removed. Transfer the carbon tetrachloride solution to a weighed flask; evaporate off the solvent and dry the flask at 95-100 deg. cent.; cool in a desiccator and weigh. Continue to dry until constant weight is obtained.

Free Sulphur

22. Add two grams potassium nitrate to the aqueous solution and washings from the ethereal separation of the unsaponified material. Evaporate to dryness in a silver or nickel dish and heat to quiet fusion, avoiding contamination with sulphur fumes. Transfer with cold water to a beaker, neutralize with hydrochloric acid; add 2 cu. cm. concentrated hydrochloric acid; filter and wash, making a volume of 200 cu. cm. Heat to boiling and add slowly a slight excess of hot barium chloride solution. Allow to stand over night, filter, wash, ignite, weigh the barium sulphate and calculate to sulphur.

Definition of Terms Describing Components of Acetone Extract

23. The difference between the acetone extract and the free sulphur shall be called the Organic Extract.

24. The difference between the organic extract, and the unsaponifiable material shall be called the Saponifiable Acetone Extract.

25. The sum of the hydrocarbons A and B shall be called the total Waxy Hydrocarbons.

26. The difference between the unsaponifiable material and the waxy hydrocarbons shall be called Unsaponifiable Resins.

Chloroform Extract

27. Extract continuously, the residues from both of the acetone extractions (without necessarily removing the acetone that may be on them), for four hours with 60 cu. cm. chloroform. Unite the extractions in a weighed flask, using hot chloroform to rinse the flasks. Distill off the solvent and dry the flask and contents for two hours at 95-100 deg. cent. Cool in a desiccator and weigh. Continue to dry for one-hour periods until constant weight is obtained. In drying, place the flask on its side but at a sufficient angle from the horizontal so that the extract does not appreciably run down the side of the flask. (If it is needful to wait after the acetone extraction, before starting the chloroform extraction, the sample must be kept in a vacuum of at least 50 mm. of mercury.)

Alcoholic Potash Extract

28. Dry the residues from the chloroform extractions at 50-60 deg. cent. until the odor of chloroform can no longer be detected; unite the residues from the two 2 g. samples in a 200 cu. cm. Erlenmeyer flask. Add 100 cu. cm. alcoholic potash solution and boil for four hours under a reflux condenser. Filter the solution by decantation through an 11 cm. hardened filter paper into a beaker and wash twice, using each time 25 cu. cm. hot absolute alcohol and then wash thoroughly with hot water. Wash any rubber on the filter paper back into the original flask and reserve this for the determination of rubber hydrocarbons. Evaporate the solution to approximate dryness, take up in warm water and transfer to a separatory funnel. Acidify with 30 cu. cm. of 5 N hydrochloric acid, using this to rinse the beaker. Add sufficient water to make the bulk of the solution 100 cu. cm. When cool add 40 cu. cm. ether, using it to rinse the beaker in 20 cu. cm. portions. Shake the aqueous and ethereal solutions thoroughly. After complete separation, draw off the aqueous solution and treat in another separatory funnel, with a fresh 20 cu. cm. portion of ether. Continue to shake the aqueous solution with fresh portions of ether until a colorless portion has been obtained, then shake out twice more. Unite the ethereal solutions and wash with successive additions of water, continuing twice after the water shows no acid reaction. Filter through a plug of extracted cotton into a tarred flask, wash the filter and funnel with ether, evaporate the ether without boiling and dry the residue at 95-100 deg. cent.; cool in a desiccator and weigh. Continue to dry until constant weight is obtained.

Rubber Hydrocarbons

29. Add to the flask containing the rubber residue from the alcoholic potash extraction, sufficient water to make the total volume of the solution 125 cu. cm. and then add 25 cu. cm. concentrated hydrochloric acid. Heat for an hour at 97-100 deg. cent. Decant the supernatant liquid through a hardened filter paper on a Buchner funnel 7 cm. diameter, using suction; wash the residue with 25 cu. cm. hot water and decant. (While a Buchner funnel is recommended, it is permissible to use an 11 cm. hardened filter paper with platinum cone, in a 60 deg. funnel). Perform this entire treatment with water and hydrochloric acid, three times and save the first and second decantations for the "organic matter" test described in section 36. The rubber at this stage should be white and practically free from black specks of undissolved fillers; if not, continue the acid treatment until the black specks disappear. (If carbon is present, all the particles of rubber will be greyish, bluish, or black, depending on the form and quantity of carbon used. Black specks in light particles of rubber usually indicate the presence of lead sulphide which must be removed to prevent the formation of lead sulphate on igniting the residue *C*.) Add 150 cu. cm. hot water to the flask and let stand on a steam bath or hot plate for half an hour and decant through the filter paper. Return to the flask any rubber that goes on the filter paper. Repeat until the washings are free from chlorides. (See section 36). Transfer all the rubber in the flask to the filter paper and dry as much as possible by suction. Wash the rubber with 50 cu. cm. of 95 per cent alcohol, using suction. Transfer the entire residue to a

weighing bottle. Dry at 95 to 100 deg. cent. for an hour, cool in a vacuum dessicator under reduced pressure and weigh. Dry for a half hour, cool and weigh, repeating this process until either constant weight is reached or the weight starts to increase. Let this weight be represented by C. On a portion D of this residue C determine the ash E according to section 30 and the sulphur F in the ash E. Determine the sulphur H in another portion G of residue C. Make all sulphur determinations as described under Total Sulphur.

30. Place about 0.5 g. of residue C into a weighed porcelain crucible. Let the weight of residue be represented by D. Heat gently, gradually driving off the volatile matter. When the crucible has ceased to smoke, raise the temperature gradually to between 450 and 500 deg. cent. until all organic matter has been burned away, which is usually indicated by the ash becoming white. (An electric muffle furnace with pyrometer is recommended for this purpose). Cool in a desiccator and weigh, the weight of ash being represented by E in the formula for rubber hydrocarbons. Make sulphur test on ash by the method described under Total Sulphur. If, however, $50 \times C \times E$ is not over unity, the determination of sulphur in the ash may be omitted and F assumed to be zero.

Then,

$$\text{Rubber Hydrocarbons} = \frac{100\ C}{4}\left[1 - \frac{E-F}{D} - \frac{H}{G}\right]$$

expressed as a percentage of the total sample.

Total Sulphur

31. Place a 0.5g of rubber in a porcelain crucible of about 100 cu. cm. capacity. Add 20 cu. cm. nitric-acid-bromine reagent, cover the crucible with a watch glass, and allow to stand for one hour. Heat very carefully for an hour, remove the cover, rinsing it with a little water, and evaporate to dryness. Add 5g. of the $KNO_3 - Na_2CO_3$ fusion mixture, and 3 to 4 cu. cm. of distilled water. Digest for a few minutes, and then spread the mixture half way up the side of the crucible to facilitate drying. Dry on a steam bath or hot plate. Fuse the mixture, using a sulphur-free flame until all the organic matter has been destroyed and the melt is quite soft. Allow to cool, place the crucible in a 600 cu. cm. beaker, and cover with water. Digest three or four hours on the steam bath. Filter into an 800 cu. cm. beaker, washing thoroughly with hot water. The total volume should be about 500 cu. cm. Allow to cool, add 7 to 8 cu. cm. concentrated hydrochloric acid to the filtrate, and heat on the steam bath. Test the solution for acidity with congo paper and add 10 cu. cm. of hot barium chloride solution. Allow to stand over night, filter, wash, weigh the barium sulphate, and calculate to sulphur.

Specific Gravity

32. The specific gravity shall be the ratio of the weight of a given volume of the compound, to the weight of an equal volume of water, both at 20 deg. cent. Cut strips of the largest practicable size from the conductor and use about 5 g. for the sample. Determine the specific gravity in the usual manner by means of a specific-gravity bottle. Care must be taken that no air bubbles adhere to the sample.

Checks

33. Specific gravity determinations shall check within 0.01. The other duplicate determinations shall check within the following limits expressed as percentages of the original sample.

Determination	Check
Acetone Extract	0.10
Saponifiable Acetone Extract	0.10
Unsaponifiable Resins	0.10
Waxy Hydrocarbons	0.10
Free Sulphur	0.05
Chloroform Extract	0.10
Alcoholic Potash Extract	0.10
Rubber Hydrocarbons	0.20
Total Sulphur	0.10

Interpretation

34. The percentage of rubber shall be considered to be the sum of the rubber hydrocarbons, saponifiable acetone extract, unsaponifiable resins, chloroform and alcoholic potash extracts, expressed as percentages. If the chloroform extract is over 3.0 per cent of the rubber so calculated, subtract the excess from the rubber. If the alcoholic potash extract is over 1.8 per cent of the rubber, as first calculated, subtract this excess also from the rubber.

Red Lead

35. Dissolve 1 g. of the sample in 75 cu. cm. Xylol at a temperature of about 100 deg. cent. When the rubber is dissolved, the absence of any red particles indicates the absence of red lead. If red particles are present, filter the solution into a Gooch crucible and wash thoroughly with benzol, acetone and alcohol successively. Remove the felt and residue to a distilling flask, add 25 cu. cm. 10 per cent hydrochloric acid, and distill over the chlorine liberated by the lead peroxide, absorbing the gas in a solution of potassium iodide and starch. Not more than 0.1 cu. cm. of 0.1 N thiosulphate shall be required to titrate the iodine liberated.

Organic Fillers.

36. Transfer the first and second decantations of the hydrochloric acid solutions to a carefully cleaned porcelain dish and add 20 cu. cm. concentrated sulphuric acid. Place dish on steam bath or hot plate to drive off water and hydrochloric acid. A pronounced charring of the residue indicates the presence of organic matter soluble in water or hydrolyzed by hydrochloric acid.

Examine filter paper and rubber while decanting acid solution and again while washing free of chlorides. Some types of organic fillers not removed by water and hydrochloric acid, would be plainly visible at this point.

Place a small portion of residue *C* under a microscope and examine for fibrous and other characteristic organic material. If organic fillers are indicated and not clearly proven by this test, place 1 g. of the organic sample in a beaker, add 75 cu. cm. Xylol and heat on hot plate until the rubber is dissolved. Decant Xylol solution and wash residue with ether several times by decantation. Dry residue and examine under the microscope.

Statement of Results

37. The results of the analysis shall be stated in the following form:

per cent

Acetone extract..............................
Saponifiable acetone extract.......................
Unsaponifiable resins..........................
Waxy hydrocarbons...........................
Free sulphur...............................
Chloroform extract...........................
Alcoholic potash extract........................
Total sulphur..............................
Rubber..................................
Color of acetone extract (60 cu. cm. vol.)...............
Fluorescence in acetone extract solution (present or absent)
Hydrocarbons *A* (consistency and color)................
Hydrocarbons *B* (solid or liquid)....................
Color of chloroform extract (60 cu. cm. vol.)............
Carbon (present or absent)........................
Organic fillers (present or absent)...................
Red lead (present or absent).......................
Specific gravity.............................
Sample braided or not..........................

PART IV—EXPLANATION OF SPECIFICATION

1. Experience has shown that compounds of the grade which contains only good Hevea rubber, may be relied upon to be more permanent than those made of rubber of other grades. It is not affirmed by the committee that a compound which conforms with this specification, is necessarily permanent, or that a better compound cannot be made, but it is believed that enforcement of the specification will limit the use of inferior materials and that it will put the manufacturers more nearly upon an equality of endeavor, where they can use their experience to obtain the best results. Used in connection with the analytical procedure, the specification will enable purchasers to order a good compound and to ascertain with a greater certainty than heretofore, whether the material received, represents the compound specified.

2. The term Hevea applied to rubber means rubber from the Hevea Brasiliensis tree whether wild or cultivated and regardless of the locality in which it has been grown. Para rubber is Hevea rubber of the kind originally shipped from the port of Para, Brazil, and comes in several grades. The rubber required by this specification should be Hevea rubber of good quality, such as fine Para or best quality plantation rubber.

3. Carbon is excluded not only because it is considered, by some purchasers, to be deleterious, but because it interferes with the determination of rubber hydrocarbons.

4. Red lead is excluded because of the possibilities of its deleterious effects on the rubber.

5. Ozokerite is prohibited because the acetone extract obtainable from it interferes with the separation of the acetone extract obtainable from the rubber, thereby vitiating the assay of the rubber extract. This prohibition is unimportant to the manufacturers, as ceresine, which is permitted, is the essential constituent of ozokerite.

6. An upper limit is placed upon the rubber in order to prevent the attainment of electrical and mechanical strength by the use of an extra quantity of inferior rubber whose lasting qualities might not be satisfactory.

7. The hydrocarbons are limited owing to their tendency to separate from the compound and thus possibly cause porosity.

8. The free sulphur is limited because an excessive amount may be deleterious.

9. The maximum limit on the saponifiable acetone extract is to prevent the use of raw or reclaimed rubber with high saponifiable extract. The minimum limit assists in forcing the use of Hevea rubber, since it is characteristic of the acetone extract from Hevea rubber to be largely saponifiable.

10. The unsaponifiable resins are limited because a low proportion of unsaponifiable resins is characteristic of Hevea rubber. A high result might be due to the presence of reclaimed rubber.

11. The chloroform extract is limited, first to prevent the use of bituminous substances, and second, to limit depolymerized and undercured rubber.

12. The alcoholic potash extract is limited to prevent the use of saponifiable rubber substitutes.

13. The specific gravity is limited to reconcile the specification of ingredients by weight with the practise of purchasing material by volume.

14. Fluorescence of the acetone solution is prohibited as it indicates the presence of bituminous substances, rosin oil, or mineral oils.

15. The color of the acetone extracts is specified to conform with the normal color of the extract from Hevea rubber. A darker color indicates adulteration or an inferior grade of rubber.

16. The hydrocarbons are required to be solid in order to prevent the use of oils and paraffine of low melting point. The shade required is that obtained from paraffine wax or ceresine. If hydrocarbons *B* are liquid this would indicate reclaimed rubber softened with mineral oil, or paraffine of low melting point.

17. The color of the chloroform extract is specified to conform with the color of dissolved gum in minute quantities. The presence of bituminous substances would be indicated by a brown or black color.

18. It would be desirable that the sulphur of vulcanization be limited to exclude reclaimed rubber, which contains the sulphur of its previous vulcanization, but the committee has not yet developed an acceptable method for determining this quantity. It is, therefore, confronted with the choice of either placing a limit on the total sulphur or giving up the attempt to exclude shoddy by sulphur limitation. Option is therefore given to the purchaser to insert or omit the limit on total sulphur. Such insertion will at times exclude reclaimed rubber and the committee believes it possible to make a suitable compound with this limitation. The com-

mittee thinks that a sulphur limit positively excluding reclaimed rubber, would place too great a hardship, in other ways, on the manufacturers. Where the specification is used with no total sulphur limit, the use of many kinds of, or much, reclaimed rubber, will be guarded against by the limits of the various components of the acetone extract. When the limitation on total sulphur is omitted, sulphur-bearing fillers, which possess certain advantages, may be used.

19. This specification should be supplemented by appropriate elasticity and tensile strength tests, in order to add to the assurance that good rubber has been used and that the vulcanization process has been properly carried out; also by appropriate electric stress and resistance tests, to assure proper insulating qualities and homogeneity of structure. The exact value of the limits for these tests will depend upon the use to which the material is to be put.

PART V—EXPLANATION OF PROCEDURE

General

1. The tentative report of the committee, presented in October, 1913, provided for the determination of the percentage of rubber present by the method of difference. The mineral fillers were determined by the terebene solution method. Results obtained in the use of this method showed that it gave inaccurate results on some compounds. The committee therefore determined to abandon it and to find a suitable substitute. It is believed that the method now recommended will satisfactorily solve the problem.

2. The most feasible means of limiting the kind of rubber was considered to be the determination of the saponifiable and unsaponifiable resins. These are fairly constant characteristics of the resins of Hevea rubber, and of compounds made from the same. Other methods, such as the determination of the saponification number and the optical activity of the resins, were thought to be unpractical.

3. The method as developed is applicable to the analysis of any pure rubber compound containing only mineral matter with or without ceresine or paraffine wax, regardless of the kind or amount of rubber, and can be used in conjunction with other specifications provided the limits are changed to correspond with the amount and kind of rubber desired, and due consideration is given to interfering mineral matter. When applied to a compound without ceresine or paraffine wax the unsaponifiable acetone extract is the unsaponifiable resins.

4. The method has been definitely described, to make it certain that experienced chemists may obtain concordant results. The interpretation has been rigidly defined, obviating any ambiguity as to the meaning that will be assumed, even though this sometimes appears to be arbitrary.

Sample

5. In order to obtain uniform results, the committee has established by experiment that a definite method of sampling has to be adopted and that for all extractions the sample must be reduced in a prescribed manner to at least an approximately similar degree of fineness. For this reason the procedure specifies a definite type of grinder obtainable in two forms, and also specifies definite sieves.

Extraction Apparatus

6. The committee has proved that the extraction apparatus used by different chemists must be of exactly the same form and the same size. It was also proven that small samples in the apparatus give the maximum results and that the rate of extraction is dependent upon the amount of solvent and its temperature as it passes through the sample. The apparatus finally adopted combines the advantages of several forms that were studied and together with simplicity of operation and adjustment to uniform conditions, gives practically complete extraction when used as specified. A number of other variations that might have a possible effect upon the amount of extract, were tried but found to be inappreciable.

Acetone Extraction

7. The extraction is made within 24 hours of the preparation of the sample, so obviating any appreciable oxidation. Two samples are extracted and united, so that a larger amount of extract may be obtained for the subsequent separations, and the extraction apparatus kept within a convenient size. Hot chloroform is used to facilitate the complete transference of the extract. The flasks are placed on their sides when drying, to hasten the emission of the solvent and thus reduce chance of volatilizing, through longer heating, some of the more volatile constituents of the extract. Drying in vacuo at room temperature, does not remove all the moisture if paraffine is present and such drying with heat or at 100 deg. cent. in an inert gas, presents no practical advantage over the method given.

Separation of the Acetone Extract

8. The method given was developed so that all the desired constituents could be determined on one sample.

9. Emphasis is laid on thorough extraction of the unsaponifiable material and the retention of the flocculent material with the ethereal solution. This latter material is not soluble in either ether or water, but it was proven that if such as was chloroform-soluble was included in the unsaponifiable material, the subsequent determination of the hydrocarbons would be more exact. A portion of this flocculent material is insoluble in chloroform.

10. The hydrocarbons are determined in two places, making an approximate separation between the solid and the liquid ones, if both are present. The first hydrocarbons *A* are those insoluble in the solvent at a low temperature. The presence of unsaponifiable resins in the solution prevents the more complete freezing out of the hydrocarbons, but the remainder is obtained after treatment of the resins with sulphuric acid. In this way, chance of loss through the action of the acid has been largely eliminated.

11. The method for free sulphur gives all the sulphur in the acetone extract with the exception of negligible amounts which may be in the unsaponifiable material. It was proven that the results agree with determinations made directly on other acetone extracts.

12. The saponifiable and unsaponifiable resins are obtained by difference.

Chloroform Extraction

13. The chloroform extraction should be made at once after the acetone extraction, or the sample put in a vacuum, so as to avoid the danger of an abnormally high extract. When the extract is dried as specified, constant weight is obtained before any appreciable oxidation occurs. If bituminous substances are present, that portion which has not been extracted by the acetone, will be largely soluble in chloroform and can be readily distinguished by its color. The amount of extract is also affected by the presence of uncured and inferior rubber. A properly cured Hevea compound will always give a little extract with chloroform, which varies somewhat with the method and conditions of cure.

Alcoholic Potash Extraction

14. The alcoholic potash extraction is the usual saponification process for obtaining the fatty acids of rubber substitutes. The total amount of such substitutes is not obtained, but if any appreciable amount is present, the value will exceed that of the limit allowed. When no substitutes are present, this determination always yields a small amount of extract from Hevea rubber.

Rubber Hydrocarbons

15. Methods for the determination of the percentage of rubber are of two kinds, the direct and the difference methods. The committee adopted a difference method after trial of various methods, both direct and indirect.

16. The difference methods are those in which the rubber is removed and the residue weighed. This may be done in either of two ways; by the use of solvents, or by ignition. The early work of the committee was largely along the line of removing the rubber by means of solvents. Many kinds and probably every class of rubber solvents were tried. Some did not completely dissolve the rubber at low temperatures and ordinary atmospheric pressure; others appeared to dissolve the rubber, but formed a colloidal solution holding some of the fillers, which could neither be filtered nor centrifuged clear of mineral matter. Many of them were so time-consuming as to render them worthless, even if accurate results could be obtained. The solvent method given in the Preliminary Report was found to give inaccurate results with compounds containing much litharge or zinc oxide, but gave very good results on most classes of compounds if xylol, instead of terebene is used as the solvent. It has since been demonstrated, however, that it is practically impossible to obtain correct results on an important class of compounds and that method was, therefore, abandoned.

17. Ashing the compound gives fairly accurate results provided no volatile or decomposable fillers are included. This, however, cannot be assumed to be the case. In the method which the committee recommends, these objectionable fillers are largely removed before the compound is ignited, and provision is made for testing those few materials which are volatile, but not removed. This method is a modification of an unpublished one devised, some years ago, by G. H. Savage.

18. In the testing of this method, compounds containing most of the known commercial inorganic fillers were analyzed. Whiting, talc, magnesium, and lead compounds and barium carbonate which are objection-

able in direct ashing do not in any way interfere with the determination of rubber by this method. A number of organic fillers were used, but these too, did not cause any great error.

19. The securing of accurate results by the method given depends largely on two things; the complete solution of decomposable fillers, and the removal of all chlorides. With these precautions, the analyst is almost certain to obtain reasonably accurate results. The formula for calculating the rubber hydrocarbons presents no difficulty if the exact quantities called for in the method are used.

20. The rubber as it is weighed under *C* contains sulphur in combination with the rubber. On ignition sulphur is driven off with the rubber. By determining the sulphur before and after ignition, the amount so lost can readily be calculated, and the proper correction made.

Total Sulphur

21. The sodium peroxide method, specified in the Committee's Preliminary Report, is widely used in the analysis of wire insulation, and is known to yield accurate results on such compounds. The liability of explosion with that method, however, renders it somewhat objectionable.

It will be noted that the bromine-nitric-acid method which is now specified does not require the dehydration and separation of silica. If the filtrate after the fusion and extraction with water, is acidified in the cold, and after the precipitation of the barium sulphate the solution is not permitted to concentrate to a relatively small volume, any silica which is in solution will remain dissolved. The elimination of this step by proper precautions saves considerable time without in any way interfering with the accuracy of the determination.

Interpretation of Results

22. Emphasis is laid on the method of calculating the results. The saponifiable acetone extract and the unsaponifiable resins are considered to be parts of the rubber. The chloroform and alcoholic potash extracts, when within the limits specified, are also so considered. Any quantity in excess of these limits is assumed to be due to foreign substances or in case of chloroform extract, to undervulcanized rubber. No allowance is made for the ash in the raw rubber, as it is considered to be negligible. This method of calculation has to be adopted if the rubber found is to agree with that originally put into the compound.

Moisture

23. A determination of moisture is not given, as electrical tests will detect its presence if in excess. If electrical tests are required, the error introduced by the omission of this determination is very small.

Note:—With a procedure of this length it is impossible to explain every detail without undue elaboration, and the committee wishes to point out that while to experienced chemists the procedure may seem over burdened by detail, yet every specified detail was found necessary in order that the conditions essential to accurate and consistent work might be reproduced by all chemists using the procedure. For this reason it is extremely important that all instructions be observed, even if their significance is not perceived by the individual chemist. It will probably be found that even with the instructions properly observed, some experience will be needed to apply the method successfully.

PART VI—LIST OF IMPORTANT SPECIFICATIONS CONTAINING THE JOINT RUBBER INSULATION COMMITTEE'S CHEMICAL CLAUSES OR ANALYTICAL PROCEDURE

American Electric Railway (Engineering) Association:
  Standard Specification for Rubber Insulated Wire and Cable.

American Society for Testing Materials:
  Proposed Specifications for Insulated Wire and Cable; 30-per cent Hevea Rubber.

Association of Railway Electrical Engineers:
  Standard Specifications for Wire and Cable.

Interborough Rapid Transit Co., Motive Power Department, New York:
  Specification No. 2.

New York Central Railroad Co. Electrical Department:
  Specification No. 300.

Panama Canal:
  Office of General Purchasing Agent, Circular No. 1038.

Signal Corps, U. S. Army:
  General Specification No. 581—A., etc.

A PRELIMINARY REPORT

Prepared for Submission to its Principals

BY

THE AMERICAN COMMITTEE ON ELECTROLYSIS

APPOINTED BY

National Engineering Societies
and other
Interested Associations and Corporations

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PREFACE.

Those familiar with the history of the electric railway industry in the United States in the early 90's and subsequently for a decade, will recall the great rapidity with which the electric railway was developed and the litigation that resulted between the gas and water companies and the electric railway companies over the introduction into the field of the electric railway using a grounded return circuit. The utility companies whose properties were threatened with damage from electrolysis due to these grounded return circuits of the railway companies, attempted by all legitimate means to prevent the acceptance of the grounded return circuit, with the result that in one or two cases,—for instance, in the city of Cincinnati, a complete metallic overhead return circuit was adopted and is still in operation, but the electric railway operated with a grounded return circuit in connection with the overhead trolley became the standard, and rapidly spread throughout the country, and still remains the standard for electric traction systems.

At first when the electric railway systems were small, and light cars were used, the quantity of current flowing through the rails was not large, and the possibility of damage from electrolysis was comparatively small, but as the systems were extended and the weight and number of cars greatly increased, the problem became much more serious, and began to demand special attention. It is only within the past four or five years that the subject has been sufficiently well understood by engineers generally to make it probable that their opinions could be made to agree upon standard methods for the prevention or adequate mitigation of electrolysis.

At the present time, due to the fact that the grounded return circuit system has been so long established and so extensively adopted, with the result that millions have been invested in copper for supplemental rail return circuits, the engineers now endeavoring to seek a solution of the question find themselves confronted with the problem not only how best to design and install a new system to prevent damage from electrolysis, but also what can be done with the electric railway systems as they exist in cities today.

While recourse to the courts has always been open, the proving in court of the precise amount of damage that has been occasioned by electrolysis, as distinct from other causes, and accurately proportioning such damage between various electrical companies, has made the fixing of responsibility extremely difficult. In view of this unsatisfactory condition it was thought best by the National Societies representing those connected with the various utilities involved to take up the subject comprehensively and endeavor, if possible, by co-operation among themselves and with other interested associations and corporations to gather and classify information, and if then found feasible to agree upon and recommend methods which without being financially prohibitive will nevertheless practically eliminate damage from electrolysis.

The American Institute of Electrical Engineers with this object in view invited the following bodies to officially appoint representatives to serve upon a committee for which the name The American Committee on Electrolysis was finally adopted:

American Electric Railway Association.
American Gas Institute.
American Institute of Electrical Engineers.
American Railway Engineering Association.
American Telephone & Telegraph Company.
American Water Works Association.
National Bureau of Standards.
National Electric Light Association.
Natural Gas Association.

The first meeting of the Committee was held in the Directors' Room, American Institute of Electrical Engineers, 33 West 39th Street, New York City, May 27th, 1913, to make preliminary arrangements, and the second meeting held at the same place on February 25, 1914, resulted in the selection of a permanent chairman and secretary, and the appointment of the various sub-committees.

The result of the work of these sub-committees is embodied in the various sections of the accompanying report.

Owing to the complexity of the subject and the need for thorough discussion in the several technical bodies, and for further investigation by the interests involved the Committee has thought best not to attempt to issue a final report at the present time, but has endeavored to present the subject in this preliminary report by such statements of fact as its members can, at this time, unanimously agree upon, with the expectation that, after the consideration of these statements of fact by the bodies whom the members of this committee represent, and such further investigation as may be necessary by the Committee, a report will ultimately be prepared, embodying principles, rules and recommendations which will form a basis for solving this complicated problem.

New York City,
September 21st, 1916.

PRELIMINARY REPORT.

THE AMERICAN COMMITTEE ON ELECTROLYSIS.

GENERAL INDEX.

PAGE

PREFACE: A General Statement of the Scope of the Work. 1686

I: PRINCIPLES AND DEFINITIONS:

A. ELECTROLYSIS IN GENERAL:

1. Electrolysis 1693
2. Electrolyte, Electrode, Anode, Cathode 1693
3. Amount of Chemical Action (Faraday's Law) 1693
4. Cause of Current Flow 1694
5. Electrolysis by Local Action 1694
6. Anodic Corrosion 1694
7. Secondary Reactions 1694
8. Cathodic Corrosion 1695

B. ELECTROLYSIS OF UNDERGROUND STRUCTURES:

9. General 1695
10. Self Corrosion 1695
11. Acceleration of Local or Self Corrosion 1696
12. Coefficient of Corrosion 1696
13. Anodic and Self Corrosion 1696
14. Passivity 1696
15. Polarization Voltage 1696
16. Alternating or Frequently Reversed Direct Current 1697
17. Action on Underground Metallic Structures 1697
18. Stray Current 1698
19. Electrolysis Mitigation 1698
20. Electrolysis Surveys 1698
21. Overall Potential Measurements 1698
22. Potential Gradients 1699
23. Positive and Negative Areas 1699
24. Drainage Systems 1699
25. Uninsulated Track Feeder System 1700
26. Insulated Track Feeder System 1700

II: METHODS OF MAKING ELECTROLYSIS SURVEYS:

A. GENERAL:

27. General Principles of Electrolysis Surveys 1701
28. Electric Railways 1702
29. Earthed Piping Systems 1704
30. Underground Cable Systems 1708
31. Bridges, Buildings and Other Earthed Structures 1710
32. Steam Railway Rails 1711
33. General Survey Practices 1712
34. Application of Remedial Measures—Resurveys 1716

B. APPARATUS:

PAGE
35. Portable Measuring Instruments.........1718
36. Recording Instruments.........1719
37. Normal Electrode.........1720
38. Earth Ammeter.........1720
39. Testing Electrodes.........1723

C. RECORDS AND REPORTS:

40. General.........1723
41. Electric Railways.........1725
42. Piping Systems.........1725
43. Cable Systems.........1725
44. Bridges and Buildings.........1726
45. General Conditions.........1726

III: AMERICAN PRACTICE:—General

A. MEASURES APPLIED TO RAILWAYS:

46. Insulation.........1727
  (a) Complete Insulation.........1728
  (b) Substantial Insulation.........1728
  (c) Partial Insulation.........1728
47. Reduction of Track Voltage Drop.........1729
  (a) Bonding.........1729
  (b) Cross-bonds.........1730
  (c) Conductivity and Composition of Rails.........1731
  (d) Reinforcement of Rail Conductivity.........1732
  (e) Use of Additional Power Supply Stations and Distribution of Load.........1733
48. Three Wire Systems.........1735
49. Reversed Polarity of Trolley System.........1736
50. Booster System.........1737
51. Interconnection of Railway Return Circuits.........1738
52. Use of Alternating Currents.........1738
53. Insulated Track Feeder System.........1739

B. MEASURES APPLIED TO AFFECTED STRUCTURES:

54. Insulating Joints in Iron Pipes and Cable Sheaths.........1741
55. Insulating Pipes, Cables and Structural Steel from Earth.........1745
56. Shielding or the Use of an Auxiliary Anode.........1748
57. Drainage of Earthed Metallic Structures.........1749
  (a) Lead Sheathed Telephone and Power Cables.........1749
  (b) Pipe Systems.........1750
  (c) Structural Steel.........1751

C. PATENTED PROTECTIVE SYSTEMS:

58. Foreign and Domestic Patents.........1751

D. ORDINANCES AND DECISIONS:

59. Ordinances.........1751
60. Decisions by Courts.........1752

IV: EUROPEAN PRACTICE:

PAGE

A. GENERAL:
61. Personal Investigation Necessary....1753
62. Countries Visited....1753

B. GERMANY:
63. Laws and Ordinances....1754
64. Commission Recommendations....1755
65. Construction....1755
66. Conditions....1755

C. ITALY:
67. Laws and Ordinances....1756
68. Construction....1756
69. Conditions....1756

D. FRANCE:
70. Laws and Ordinances....1756
71. Construction....1757
72. Conditions....1757

E. ENGLAND:
73. Laws and Ordinances....1757
74. Construction....1758
75. Conditions....1758

F. SUMMARY AND CONCLUSIONS:
76. Germany, Italy, France, England....1759
77. Application to American Conditions....1759

G. REGULATIONS ADOPTED AND PROPOSED:
78. Germany—Earth Current Commissions' Recommendations..1761
79. France—Regulations by Minister of Public Works....1779
80. England—British Board of Trade Regulations....1781
81. Spain—Electric Legislation....1787

H. SUMMARY OF EUROPEAN CONDITIONS:
82. Present Electrolysis Conditions....1787
83. Protective Measures in Vogue....1789
    Feeders....1789
    Voltage and Current Conditions....1790
    Miscellaneous Protective Measures....1791
84. Economic Aspects of Electrolysis Problem....1795
85. Regulations and Tests....1795

I. GENERAL REMARKS:
86. Germany....1796
87. France....1797

J. STATISTICAL—OPERATING—STRUCTURAL AND TECHNICAL DATA:

PAGE
88. Table 1—Magnitude of Electric Railway Undertakings, German Empire and United Kingdom....1797
89. Table 2—Tramways Not Operated by Electricity, German Empire and United Kingdom....1798
90. Table 3—Ownership of Electric Railway Undertakings, German Empire and United Kingdom....1798
91. Table 4—Statistics of Tramways in Large Cities, German Empire and United Kingdom....1799
92. Table 5—Statistics of Tramways in Small Cities, German Empire and United Kingdom....1800
93. Table 6—Rail Bonding Data, United Kingdom....1801
94. Table 7—Use of Negative Boosters, United Kingdom....1802
95. Table 8—Distribution Systems for Tramway Feeders, United Kingdom....1802

K. CURVES AND SKETCHES:

Curve—Graphical representation of Electric Railways Statistics, United Kingdom, 1878 to 1912. (Fig. 9)....1803
Sketch—Track Construction, United Kingdom. (Fig. 10)....1804
" —Track Construction, Germany. (Fig. 11)....1805
" —German Tramway Rails. (Fig. 12)....1806
" —British Tramway Rails (Fig. 13)....1807
Curve—Rail Weight Data. (Fig. 14)....1808
Sketch—Typical Rail Bonds, United Kingdom. (Fig. 15)....1809
" —Cross Bonding Details, United Kingdom (Fig. 16)1810

L. MISCELLANEOUS NOTES:

96. Electrolysis Testing Methods....1811
97. Abstract of Laws and Regulations or Recognized Standards in European Countries....1811
98. Plan of German Earth Commission Reports....1913
99. General Comments on Reports....1814

V: BIBLIOGRAPHY: 1815

VI: APPENDICES. (Tables.)

100. Table 9. Resistance of Standard Cast Iron Pipe....1819
101. Table 10 Resistance of Standard Steel or Wrought Iron Pipe1826
102. Table 11. Resistance of Lead Cable Sheaths....1828
103. Typical Report Sheets....1829

I. PRINCIPLES AND DEFINITIONS.

A. ELECTROLYSIS IN GENERAL.

1. Electrolysis is the process by which *chemical changes are caused* by an electric current, independent of any heating effect.

> NOTE. These changes usually occur in a water solution of an acid, alkali or salt. By the passage of an electric current through it, water (containing a trace of acid) is decomposed into hydrogen and oxygen, copper is deposited from a solution of copper sulphate, silver from solutions of silver salts. Electroplating, electrotyping, and refining of metals by electrodeposition are useful applications of electrolysis in the arts. Electrolysis is involved in the charge and discharge of storage batteries, and in the operation of primary batteries.
>
> In order that electrolysis may occur, the following conditions must be present:
>
> (a) There must be a flow of electric current through a conducting liquid from one terminal to another;
>
> (b) The conducting liquid must be a chemical compound or solution which can be altered by the action of the electric current.

2. Electrolyte, Electrode, Anode, Cathode. The *electrolyte* is the solution (or fused salt) through which the electric current flows; the conducting terminals are the *electrodes*; the terminal by which the current enters the solution is the *anode*; the terminal by which it leaves is the *cathode*.

> NOTE. The chemical changes caused by the current may affect both the electrolyte and the electrodes. In the case of a solution of copper sulphate with copper plates as electrodes, copper is removed from the anode by the current and carried into solution; an equal amount of copper is deposited upon the cathode. In general, the metal travels with the current toward the cathode.

3. Amount of Chemical Action. (*Faraday's Law*). The amount of chemical action taking place at the anode and also at the cathode (as expressed by Faraday's law) is proportional to (1) the strength of current flowing, (2) the duration of the current, and (3) the chemical equivalent weights of the substances.

> NOTE. Otherwise expressed, the quantity of metal or other substance separated is proportional to the total quantity of electricity passing and the electro-chemical equivalent of the substance or substances concerned. The electrochemical equivalent of a metal is proportional to its atomic weight divided by its valence. Faraday's law is so exactly realized in practice under favorable conditions that it is used as the basis for the definition of the international ampere, one of the fundamental electrical units.

4. Cause of Current Flow. The current flowing through the electrolyte may be due (1) to an external electromotive force or (2) to the *difference of potential* due to the use of electrodes of different materials or to solutions of different concentrations.

> NOTE. The first case is illustrated by electrolysis of dilute sulphuric acid using two lead plates and an external battery; the second by the electrolysis of the same solution using a zinc and a copper plate, which touch each other inside or outside the solution. The first occurs in charging a storage battery; the second in the discharging of a primary battery or a storage battery.

5. Electrolysis by Local Action. Instead of two plates of different metals the same result may follow with *one plate if* it is chemically impure or otherwise heterogeneous, when immersed in dilute acid.

> NOTE. Such a plate excites local currents and a loss of metal occurs at all the anode areas. This *local action* causes impure zinc to dissolve rapidly in a solution which has no action on pure zinc.

6. Anodic Corrosion is the term applied to the loss of metal by electrolysis at the anode.

> NOTE. When iron is anode the iron is carried into solution by the current, the first product being a salt of iron, the nature of which depends upon the character of the electrolyte. In dilute sulphuric acid, ferrous sulphate is formed, in hydrochloric acid, ferrous chloride, etc. These first products of the electrolysis are frequently modified by *secondary reactions*.

7. Secondary Reactions are the chemical changes which occur at or near the electrodes, by which the primary products of electrolysis are converted into other chemical substances, and are sometimes followed by other reactions.

> NOTE. Ferrous hydroxide formed by the union of iron with hydroxyl ions set free at the anode, is subsequently converted into iron oxide due to the reactions with oxygen dissolved in the electrolyte. When lead is cathode in an alkali soil or solution, the alkali metal (such as sodium or potassium) reacts with water at the cathode and forms alkali hydroxide, setting free hydrogen. This hydroxide may (especially after the current ceases) react with the lead chemically and form lead hydroxide, which in turn may combine with carbon dioxide, forming lead carbonate.

8. Cathodic Corrosion is the term applied to the corrosion due to the secondary reactions of the cathodic products of electrolysis, as described in the preceding paragraph. The metal of the cathode is not removed directly by the electric current but may be dissolved by a secondary action of alkali produced by the current.

> NOTE: The anodic corrosion is more common and more serious; cathodic corrosion, however, sometimes occurs on lead and other metals that are soluble in alkali. Cathodic corrosion never occurs in the case of iron.

Vol. 35
1916

B. ELECTROLYSIS OF UNDERGROUND STRUCTURES.

9. General. In the electrolysis of gas and water pipes, cable sheaths, and other underground metallic structures, and the rails of electric railways, the moisture of the soil with its dissolved acids, salts, and alkalis is the *electrolyte*, and the metal pipes, cable sheaths and rails are the *electrodes*.

> NOTE. Where the current flows away from the pipes, the latter serve as anodes and the metal is corroded. Metal or gas or alkali, according to the nature of the soil, will be set free at the cathode.

10. Self Corrosion is the term applied when a pipe or other mass of impure or heterogeneous metal buried in the soil is *corroded due to electrolysis by local action*.

> NOTE. This is called "self corrosion" because the electric current originates on the metal itself, without any external agency to cause the current to flow. Self corrosion may also be due to direct chemical action.

11. Acceleration of Local or Self Corrosion. Self corrosion is accelerated by the presence of *acids* or *salts* in the soil water which lower its resistance as an electrolyte, and also by *cinders, coke* or other conducting particles of different electric potential which augment the local electric currents. In the latter case the metal need not be heterogeneous.

> NOTE. A pipe may be destroyed in a relatively short time by self corrosion or local action if buried in wet cinders or in certain soils.

12. Coefficient of Corrosion. The coefficient of electrolytic corrosion, (sometimes called corrosion efficiency) is the quotient of the total loss of metal due to anodic corrosion (after deducting the amount of self corrosion if any) divided by the theoretical loss of metal, as calculated by Faraday's law, on the assumption that the corrosion of the anode is the only reaction involved.

> NOTE. In practice it is found that the coefficient of corrosion varies widely from unity, being sometimes as low as 0.2 and sometimes even above 1.5, but commonly between 0.5 and 1.1.

13. Anodic and Self Corrosion. Anodic corrosion due to external currents and *self corrosion* due to local action may occur simultaneously, and the *former may accelerate the latter.*

> NOTE. Hence the corrosion due to a given current plus the increased self corrosion induced by that current may give a greater total corrosion than called for by Faraday's law. This explains how the coefficient of corrosion may exceed unity.

14. Passivity is the name given to the phenomenon in which a current flows through an electrolyte without producing the full amount of anodic corrosion which would occur under normal conditions.

> NOTE. This restricted definition of passivity has regard only to its effect in electrolysis. Many conditions affect the degree of passivity attained, an initial large current density being favorable to it. Plunging iron into fuming nitric acid renders it temporarily passive. A satisfactory explanation of passivity has not been given.

15. Polarization Voltage (sometimes called polarization potential) is the temporary change in the difference of potential between an electrode and the electrolyte in contact with it due to the passage of a current to or from the electrode. This change in potential difference, is due to the change in the conditions of the surface of the electrode or change in the concentration of the electrolyte (or both), and under some conditions is approximately proportional to the current flowing, but in many cases is not so proportional. The magnitude of the polarization voltage also depends on the material of the electrode, the nature of the electrolyte and the direction of the current.

16. Alternating or Frequently Reversed Direct Currents. If alternating currents (or frequently reversed direct currents) flow through the soil between pipes or other underground metallic structures, the metal removed during the half cycles when a pipe is anode may be *in part replaced* when it is cathode. Hence, the total loss of metal on a given pipe is less than one-half of what it would be if the pipe were an anode with direct current of the same average value in the case of frequently reversed direct current and in the case of alternating current at commercial frequency it is less than 1% and in most cases negligible. (See Section 52.)

NOTE. In slow reversals of current, the recovery effect is less, but the loss will be less than with direct current continuously in the same direction (excepting possibly where the phenomenon of passivity may affect the result).

17. Action on Underground Metallic Structures. Faraday's Law applies to electrolysis of metallic structures in soil as elsewhere, the total chemical action being proportional to the average current strength and the time the current flows and to the electrochemical equivalent of the metal or other substances concerned. Although local action and passivity affect the loss of metal and so apparently modify Faraday's law, it is still true that the total chemical action resulting from the current flow is proportional to the total current when local currents are included.

NOTE. Sometimes this chemical action is concerned only with corroding the anode; sometimes it is concerned with breaking up the electrolyte, as when the anode is a noble metal or in the passive state (as iron and lead sometimes are); sometimes both these effects occur.

The theoretical loss of lead from a lead pipe or cable sheath is 3.7 times as great as that of iron (ferrous) from an iron pipe due to the same current because of the larger electrochemical equivalent of lead.

18. Stray Current. If the railway return utilizes the grounded rails of the tracks, part of the current will flow off the rails or other grounded returns and return through other paths; the current observing the law of divided circuits; *i.e.* the current flows through all possible paths in parallel, the strength of current in each path being inversely proportional to its resistance. This statement excludes the effect of polarization on rails and underground structures, which in some cases is appreciable.

19. Electrolysis Mitigation. The two primary features of electrolysis mitigation are (1) the reduction of the flow of current through the earth and the metallic structures buried in the earth, (2) the reduction of the anode areas of such structures to a minimum, where the current is not substantially eliminated in order to reduce the area of destructive corrosion as far as possible.

> NOTE: The current in the underground metallic structures will be decreased, other conditions remaining the same, by (1) increasing the conductance of the return circuit, (2) increasing the resistance of the leakage path to earth, (3) increasing the resistance between the earth and the underground metallic structures, (4) increasing the resistance of the underground metallic structures.
>
> The anode areas of the underground metallic structures will be decreased, other conditions remaining the same, by providing suitably placed metallic conductors for leading the current out of the underground structures so that the flow of the current directly to the earth shall be minimized. This will change a portion of the anode area to cathode.

20. Electrolysis Surveys. A term applied to investigations made to determine the condition of grounded metallic structures and the soil in which they are imbedded and of the overall drops, potential gradients, local potential conditions, current densities, etc. in the railway tracks, or other grounded metallic structures, and positive and negative feeders connected to them to determine what conditions tending to produce damage exist.

21. Overall Potential Measurements. Overall potential measurements show the difference in electric potentials between points in the tracks at the feed limits of the station and the point in the tracks which is lowest in potential, and are obtained by means of pressure wires and indicating or recording voltmeters.

> NOTE: The pressure wires may be telephone or other wires utilized temporarily, or wires permanently installed for the purpose.

22. Potential Gradients. The potential gradient is the rate of change of electric potential along the rails of a track or other grounded structure in the earth, and is usually expressed in volts per thousand feet or volts per kilometer.

23. Positive and Negative Areas. Positive areas are those areas where the current is in general leaving the pipes or other underground metallic structures for the earth. Such areas are often called *danger areas*.

Negative areas are those areas where the current is in general flowing to the pipes or other underground metallic structures.

> NOTE: As the current often flows from one underground metallic structure to another, it is evident that within a positive area there are local negative areas and vice versa. Hence the terms are applied somewhat loosely, and according to which condition predominates.
>
> Besides the positive and negative areas there are areas of more or less indefinite extent in which the current flow between metallic underground structures and earth normally reverses between positive and negative values. These areas are called *neutral areas* or *neutral zones*.

24. Drainage Systems. A drainage system is one in which wires or cables are run from a negative return circuit of an electric railway and attached to the underground pipes, cable sheaths or other underground metallic structures which tend to become positive to earth, so as to conduct current from such structures to the power station, thereby tending to reduce the flow of current from such structures to earth.

> NOTE. Three kinds of drainage systems may be distinguished. (1) where direct ties with wires or cables are made between underground metallic structures and tracks, (2) where uninsulated negative feeders are run from the negative bus to underground metallic structures, (3) where separate insulated negative feeders are run from the negative bus to underground metallic structures, or a main feeder with taps to such structures.

25. Uninsulated Track Feeder System. An uninsulated track feeder system is one in which the return feeders are electrically in parallel with the tracks. Under such circumstances the cables may be operating very inefficiently as current conductors and as a means of reducing track voltage drop, particularly where voltage drops in the earth portion of the return are maintained at the low values usually required for good electrolysis conditions. (See Section **47** (d)).

26. Insulated Track Feeder System. An insulated track feeder system, sometimes called an insulated return feeder system, is one in which insulated wires or cables are run from the insulated negative bus in a railway power station and attached at such places to the rails of the track as to take current from the track and conduct it to the station, in such a manner as to reduce the potential gradients in the tracks and the differences of potential between underground metallic structures and rails, and so reducing the flow of current in underground metallic structures. (See section **53**).

> NOTE. The insulated negative feeders may run separately from the negative bus to various points in the track network, or a smaller number of cables may be used with suitable resistance taps made to tracks at various places.
>
> With this system the drop of potential in the track feeders is independent of the drop of potential in the tracks.

METHODS OF MAKING ELECTROLYSIS SURVEYS.

A: GENERAL.

27. General Principles of Electrolysis Surveys. The principal measurements made in electrolysis surveys of underground structures are measurements of the potential differences between the structure tested and all other neighboring metal structures in earth, neighboring rails, and neighboring earth, and measurements of current flow on selected sections of the structural system under test. The potential difference between the structure tested and earth affords more complete information than can be secured from the results of any other practicable class of observations. The difficulties are, however, to make these measurements so as to obtain the true potential difference between the earth and the earthed structure, and frequently also to obtain contact with earth in the immediate neighborhood of the structure tested. If an electrode is used for the earth potential measurement, not consisting of the same metal as the structure tested an error may still be introduced due to difference in the polarization potential of the two electrodes. A non-polarizable electrode has been devised by Dr. Haber, as described later in this report, but it has been used only to a very limited extent in this country. On account of the difficulties of making earth potential measurements, measurements of the potential differences between the structure that is being surveyed and neighboring metal structures are much more generally made.

Measurements of stray current flowing in selected sections of any structural system are practicable if a suitable length of the structure can be made accessible. By comparison of such measurements conclusions can be reached as to the areas in which stray currents are being taken from or delivered to the earth and as to the amounts of current which are concerned in these exchanges. Measurements of this character usually cannot be made on sections so close together as to give for many points definite values for the current flowing to or from earth on account of the high cost of the necessary excavations and permanent replacements. We have therefore included a description of the "earth ammeter" which has been used abroad, and to a limited extent also in this country, for obtaining direct measurements of current flow in the earth.

A survey of the earthed structures which are liable to electrolytic corrosion by stray currents consists in making such observations relating to their electrical condition as may determine the route followed by the stray current and its degree of concentration, thereby permitting deductions to be made relative to the extent and the intensity of the electrolytic injury to which the structures may be subjected. While measurements of potential are most frequently made (to such an extent that the term "Potential Survey" is often applied to this work), it should be borne in mind that the real object of the survey is to determine where current may flow from structure to earth or from earth to structure and the magnitude of the current flowing for each of the smallest sections into which the structure can practically be subdivided.

In discussing methods of survey, the measurements of potential and current peculiar to each class of earthed structures will first be described, together with any special observations or precautions to be taken. A discussion of the measurements of a general nature common to all classes of structures will then follow. Measuring instruments and other apparatus employed in connection with this work will be described in detail in the section devoted to apparatus.

28. Electric Railways. Before making measurements relating to an electric railway system the available information as to its extent, its construction features and particularly the arrangement of its earthed return circuit and the connections thereto should be collected. The best available maps should be procured and all information pertinent to the electrolysis investigation recorded, either by annotation on a suitably arranged map, or in some other convenient form. All electrical connections made for any purpose with the rails or other parts of the return circuit should be noted with special care, and the location of any structures to which connection is thus made ascertained and recorded.

The principal measurements to be made upon the grounded return system of an electric railway are as follows:

1. Potential differences between the point of lowest potential on the tracks, and selected points on the tracks throughout the feeding district of the station under observation.
2. Potential gradient measurements along the railway tracks to determine the difference of potential between points on the track separated from each other by distances of from 1,000 to 3,000 feet.
3. Differences of potential between all points where negative feeders or other connections between bus-bars and rail return make contact with track; also differences of potential between these points and the station bus-bar.
4. Currents carried by each separate connection between bus-bar and rail.

For most of the potential measurements listed above, it is necessary to have available insulated wires connected with all points on the railway return system, whose potential relations are to be determined, all of these insulated wires being brought to some common point so that measurements may be made between them. Where pilot wires have been installed by the electric railway, many, if not all of the points at which it is desired to make tests will be accessible without the necessity of any special preparations. Where pilot wires are not available or where it is desired to reach points not included in the pilot wire system, the most economical plan will be to procure the use of any available circuits found in the local telephone distribution system. Short lengths of insulated wire will need to be run to connect such circuits with the tracks and the testing circuits thus established can readily be brought together at some common point for measurements between them. Where neither of the above alternatives is available, wires can be installed in some temporary manner over available pole line routes to connect with the points whose potentials are to be observed. Such wires should be insulated from earth except at the point where they connect with the tracks.

When the testing circuits are established, the required potential measurements should be obtained by connecting to a voltmeter the wires leading to the two points where difference of potential is to be determined. The voltmeter should be kept in circuit and under observation for a time sufficient to insure that the normal fluctuations of the railway load have been accounted for. When long time observations of the potential difference between two points are desired, a recording voltmeter should be employed. If circuits to a sufficient number of points have been installed, the measurements of potential gradient in the tracks may be taken by connecting the proper wires at the central point to the voltmeter. If the requisite number of pressure wires for gradient tests is not available, these measurements may be obtained by carrying a suitable length of insulated wire along the track and connecting it through a voltmeter to the track at the two points between which the gradient is to be measured.

Measurements of current flowing in negative feeders or in other connections to the track return can be taken by inserting an ammeter in the circuit to be measured, when this is possible, or by taking the voltage drop along some accessible section of the connecting lead, which is sufficiently uniform in dimensions to permit of a ready calculation of its resistance. It is important that all such measurements of current should be taken either simultaneously with measurements of potential difference between the bus-bar and the track end of the connection, or under such conditions as to permit of their accurate correlation with the potential observations. A station load curve should also be obtained on account of the information which it gives as to the characteristics of the power supply.

Measurements of rail bond resistance are not necessarily a part of the work to be done in an electrolysis survey. It is, however, occasionally necessary in connection with a survey to test the resistance of particular rail bonds in order to obtain data necessary for the explanation of results obtained in making some of the regular measurements. When such tests are made, the fall of potential across the joint in the rail should be observed simultaneously in comparison with the difference of potential for some short measured length of the adjacent rail. If one of the special rail bond testing devices is not available for this work, two voltmeters can be employed and read simultaneously, or one voltmeter can be connected with a quick acting switch and employed so as to secure practically simultaneous observations. This latter method may give unreliable results unless a large number of readings are averaged.

29. Earthed Piping Systems. Before tests are made to determine the electrolytic condition of any piping system, all available information as to its extent and the characteristics of its construction should be collected and studied. The best available maps of the system should be procured and any special information of importance in connection with an electrolysis survey not noted on the maps, such as the metals of which the pipes are composed, the location of insulating joints, the relative locations of other piping, and cable systems, the location of electric railway tracks and return circuits, etc., should either be recorded upon them or arranged in some convenient form for reference.

The observations which should systematically be taken in examining a piping system are as follows:

1. Difference of potential between piping system and electric railway rails, other piping systems, cable systems, metal bridges, steam railway rails, etc., at points where these cross the piping system or come in close proximity to it. (Potential survey).
2. Measurements of potential difference between adjacent hydrants, or adjacent drip or service connections. (This will serve to give the direction of the current flowing in the pipe line and some rough indications of its amount).
3. Measurements of current flowing upon exposed sections of pipe. (Current survey).
4. Difference of potential between points on the piping system and the adjacent earth if contacts with earth can be obtained.

To make a potential survey, potential differences between the underground pipes and rails are usually measured at a number of points along every street where there are pipes and electric railway tracks. Where there are other underground pipes and lead-sheathed cable systems, it is desirable to make simultaneous measurements of potential difference between the piping system being surveyed and the neighboring pipe and cable sheaths. It is desirable to make all of the measurements of potential difference at any one point simultaneously between all structures tested. Contact with the underground pipes for these potential measurements may be made by means of service pipes, hydrants, or drip connections. The connections used for the potential measurements may be tested for electrical continuity by means of an ammeter connected between the contacts with a dry cell in series if necessary.

Measurements of potential difference between adjacent test points on the piping system should also occasionally be taken. As the resistance of pipe joints is usually not uniform, only an approximate idea of the current flowing can be obtained in this manner. The principal object of this test is to obtain an indication of the direction of the flow of current.

It is therefore desirable to make a rather large number of these tests at quite frequent intervals, since the results may be interpreted only in a general way; individual tests may be expected to vary widely, and in some cases they may even conflict. This test may be made for shorter intervals and in greater detail, where some sudden change of potential difference to earth or neighboring structures has been observed. Owing to the uncertainties as to resistance of joints it is best not to attempt to translate these voltage readings into terms of current. They may, however, be used in comparisons to assist in fixing the points for more accurate measurements of current as described in the next paragraph.

When the potential observations have been completed and transferred to a map or in some other way assembled for study, consideration should be given to them with a view to determining what parts of the piping system appear likely to be receiving substantial amounts of current from earth or passing substantial amounts of current to earth. The neutral sections of piping between positive and negative potential zones should also be located. With this information at hand sections of the piping system should be selected both in the positive and negative zones and in the neutral area at which excavations can be made and determinations of the current flowing in the pipes obtained. In selecting points for excavations, preference should in general be given to the main piping routes, but attention should also be given to any branch lines which appear likely to be receiving or delivering relatively large amounts of current. Any cases where sections of the system located within the "negative area" give positive readings to earth, should also be given preference in this study.

The method of measuring current consists in determining the fall of potential along a measured length of pipe of known dimensions. For the purpose of this measurement it will generally be found advisable to attach insulated wires permanently to the pipe and to carry them to some suitable point underneath the sidewalk from which they may be led up to the surface to terminate in service or other suitable boxes so as to be available for measurements of current in the future after the excavation has been filled. (See Fig. 1.) Tables giving the resistances of unit lengths of pipe of different diameters and materials are attached

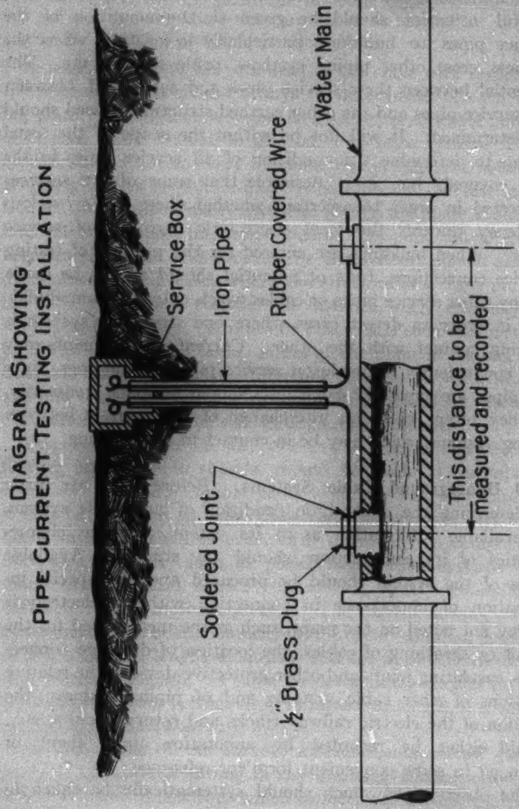


DIAGRAM SHOWING
PIPE CURRENT TESTING INSTALLATION
Service Box
Iron Pipe
Rubber Covered Wire
Water Main
Soldered Joint
½" Brass Plug
This distance to be measured and recorded

Figure 1

to this report. (See Appendix Tables 9-10). The current flowing in the pipe may be obtained by computation from the observed drop of potential and the unit resistance for the class and weight of pipe.

In addition to the observations made upon the piping system, careful attention should be given to the condition of the service pipes to buildings, particularly in locations where the services cross other piping systems, cable systems, etc. The potential between these service pipes and earth and between the service pipes and the other earthed structure crossed should be determined. It will not be within the scope of the usual survey to determine the condition of all service pipes in the area covered, but it is desirable that some of the services be tested in order to ascertain whether there is any serious tendency towards the local electrolytic corrosion of service pipes. When buildings are entered for the purpose of testing service connections, tests of potential should always be made to any other service pipes or cables which enter the same building, in order to detect cases where one structural system is making contact with the other. Current measurements may also conveniently be made on service pipes in buildings, since the pipes are exposed. Such tests should be made frequently, as they often reveal an interchange of stray current between piping systems which may be in contact in the building.

30. Underground Cable Systems. Before tests are made to determine the electrolytic condition of any cable system, all available information as to its extent and the characteristics of its construction should be studied. Available maps of the system should be procured and any special information of importance in connection with an electrolysis survey not noted on the maps, such as the metals used for the armor or sheathing of cables, the location of drainage connections, insulating joints and other protective devices, the relative locations of other cable systems and of piping systems, the location of the electric railway tracks and return circuits, etc., should either be recorded by annotation upon them or arranged in some convenient form for reference.

The observations which should systematically be taken in examining the cable system are as follows:

1. Difference of potential between the cable system and electric railway rails, other cable systems, piping systems,

metal bridges, steam railway rails, etc., at points where these cross the cable system or come in close proximity to it.

2. Difference of potential between points on the cable system and the adjacent earth.
3. Difference of potential between cables in the same subway system where they are not cross bonded.
4. Current flowing upon the cables.

In making surveys the potential of the cable with respect to the adjacent earth should always be determined at each testing point. In original surveys the greatest practicable number of testing points should be utilized. In some systems it will be desirable to test at every manhole, but in extensive networks of power cables it will ordinarily be sufficient to test at less frequent intervals in many districts, if tests are made at shorter intervals in the most important places. The potential difference between the cable and rails in the same street should also be determined, but in cases where the street railway rails parallel the cable route for a considerable distance, such tests may be made less frequently. If pipes or other earthed metallic structures run close to the cable system at the point of testing, it is desirable that the potential difference between the cable system and the other structure be determined, provided an electrical connection can be made, *e.g.*, through a hydrant, etc.

Tests to determine the direction and amount of stray current flowing on the cable sheaths should be made at appropriate intervals. In fairly simple cable systems, with few laterals, it may be sufficient to make these tests at comparatively infrequent intervals, such as every fifth manhole. In complicated networks, however, such as power distribution systems with many branches and service connections, it will generally be desirable to test more frequently. The current flowing on the cable sheath is to be calculated from the observed fall of potential over a measured length of sheath, and the known resistance of this length of sheath. A table for determining current on lead cable sheaths from voltage drop in measured length of sheath is appended. (See Table 11.)

In the course of the survey, measurements should also be made of the current flowing in any drainage connections or in any accidental connections which connect the cable system with the electric railway return if any such exist. In case insulating joints have been inserted to protect any parts of the cable system from electrolytic corrosion, measurements of the potential difference between cable sheath and earth should be made at each side of the insulating joint, and also of the difference in potential across the joint.

In a preliminary study it should be ascertained whether it is the local practice to insulate from the main cable system those branches which enter buildings. When such branches are not insulated from the main system, tests of difference of potential should be made, between the branch cable and any pipes or other cables which may enter the same building. From such tests it may be ascertained whether there are accidental contacts between the cable system and other earthed structures within buildings, and if any such are found in a portion of the total number of installations, a conclusion can then be reached as to the desirability of checking the conditions in all buidlings entered. In localities where it is the practice to insulate from the main system cable branches entering buildings, the possibility of defective insulation should be checked by measuring the potential difference between cable inside of the building and cable outside at some point beyond the supposed location of any insulating joint. Tests for differences of potential between the branch cable and other metal structures within a building can be omitted in case the insulating joint is found to be in good condition.

The condition of the bonds installed to equalize the potential of the cables entering such manhole should be observed and noted. If bonds are lacking, or if it is suspected that the condition of any bond is faulty, observations of the difference of potential between the cables should be taken and recorded.

31. Bridges, Buildings and Other Earthed Structures. Through the study of maps, etc., collected as preparatory data for surveys of piping and cable systems, information will presumably have been secured concerning the locations, and some, at least, of the structural characteristics, of the highway and railway bridges located within the area to be studied. The locations of steam railway tracks will similarly have been obtained.

In making electrolysis surveys of bridges, measurements of potential to earth should be made at each end of the metal structure. In case the bridges are crossed by electric railway tracks, piping systems or cable systems, measurements should also be made from the metalwork of the bridge to these structures to determine whether there is any difference in potential between them. Where the metalwork of the bridge structure, piers, or other intermediate supports makes contact with earth or with water, measurements of potential difference to earth or to water also should be made. The observer should follow up closely any indication of poor electrical contact between different sections of the metalwork of the bridge, or between the metalwork and any other of the earthed structures crossing the bridge which are supposed to be in good electrical contact with the metalwork.

In the course of the survey, metal frame buildings may be found in locations where it would be possible for them to collect appreciable amounts of current, either directly through the earth or indirectly through the contact of rails, pipes, or cables with the framework. If it appears that such contacts exist, measurements by the fall of potential method should be made to ascertain whether appreciable currents are flowing into the building through these contacts, if this is found to be the case tests should be made at a number of points from the building structure to ground for the purpose of determining where the current leaves the framework and whether there is any indication that appreciable damage is being done. In the case of buildings extending over a considerable area it is desirable that measurements of potentials be made from the framework to earth at a number of points, even in case no contacts are found between the metal framework of the building and other metal structures which may be carrying stray currents.

32. Steam Railway Rails. Steam railway rails, either through direct contact with electric railway rails or, in the absence of an insulating ballast, through contact with earth, are liable at times to collect and discharge appreciable amounts of stray current, and this may occur in such a manner as to be detrimental to the track rails, spikes and adjacent earthed structures. Because of this, as has already been indicated, measurements of potential to steam railway rails should be made whenever the structures that are being surveyed are in close proximity to steam railway tracks, and it is also desirable to determine directly by survey the condition of metal steam railway bridges as well as the condition of metal highway bridges. When steam railways are equipped for electric block signaling the signal battery will affect the potential of the rails. The potential due to the signaling connection is, however, practically uniform in value and can be determined through observations made at times when no stray current can be flowing. With this potential fixed, a conclusion as to the presence and amount of any potential can readily be reached.

33. General Survey Practices. All measurements, excepting 24-hour records, should be made during the period of normal load on the portions of the railway system which are suspected of being the sources of stray currents. In general, it is desirable to express the results of short time measurements in terms of "average day load" on the railway system. In localities distant from the source of railway power supply, the foregoing considerations make it necessary to take into account the presence or absence of moving cars at points beyond the testing station, especially on the tracks nearest to the structure which is being tested. In such localities the duration of a test should be extended to include at least one complete cycle of car movement, unless previous experience at other testing points in the immediate neighborhood have clearly indicated that parts of the cycle may safely be neglected. As the railway lines converge toward a common center, or as the source of railway power supply is approached, the probability of normal load condition increases but even under these conditions it is necessary for the tester to insure that the railway load conditions are substantially normal, when measurements are being made.

At a number of points observations of potential differences and of current flowing along the structure should also be made with 24-hour recording instruments and the characteristics of these currents and potentials compared with the characteristics of railway load curves. This will serve to indicate whether the current and the potential are identified with the railway source. The 24-hour averages for currents and potentials obtained at these points of measurement will also be of use in indicating what allowances should be made in the readings taken systematically at all points of the system in order to make them represent the average day conditions.

During observations of potential or current the movements of the needle in the measuring instrument should be closely watched so that the maximum and minimum readings may both be obtained as well as any change in the polarity of the potential or in the direction of the current. The observer should also bear in mind that collected results of the individual tests will be plotted on a map or otherwise compared so as to get a general idea of the conditions prevailing. When, therefore, there is reason to believe that the recorded maxima and minima are abnormal, notes should be made giving the reasons for such a belief and indicating the value which is thought to be more nearly comparable with the values obtained at other points.

In regular field survey work portable measuring instruments, will be found most suitable for the great majority of the measurements to be taken. Occasionally, however, conditions will arise under which it is desired to observe the potential or the current at some particular point for several hours and even for one or more 24-hour cycles. In the case of such long period observations recording voltmeters, millivoltmeters and ammeters will be found of great assistance and should be employed if available. Instruments of this kind are described in the apparatus section. (Sec. 35-39.)

When bodies of water or areas of swampy earth cross or are located in close proximity to earthed structures, stray current may flow from the structure to earth locally. This is particularly true if the water is brackish or salty. In case such relatively high conductive sections of the earth afford a path of lower resistance for the return of current than the structure itself, the probability of a large flow of current to earth is considerable. The flow of current from the earthed structure is not necessarily stopped when such highly conductive strata have been hidden by building over them or by filling in with surface soil. It is, in consequence, necessary to observe closely the physical geography of the areas covered by the survey and unless the observer is personally familiar with the history of the locality and the changes which have occurred, it is desirable for him to ascertain the facts from those familiar with them. If the structure under observation is accessible for tests at intervals of a few hundred feet and care is taken to make tests of potential to earth at all of these points, the presence of any condition which tends to cause the localized flow of current from the structure to earth will usually be detected. While the labor of making the survey is increased through the necessity of such frequent observations, it is preferable to include all accessible points in the original survey and to eliminate testing points in subsequent surveys when sufficient experience has been gained to indicate that greater distance between points of observation is safe.

When the electric railways in the area under investigation receive current from two or more sources of supply and there are indications that electrolytic damage is occurring at any point upon the earthed structures investigated, it may become necessary to ascertain the origin of the current causing the injury. The preliminary study of the electric railway system or systems will have included the detailed methods for distributing power, whether the trolley systems are interconnected or divided into insulated sections and whether or not all of the rails are interconnected at junctions, etc., as well as the methods of bonding and cross-bonding. If the trolley is supplied from several sources in parallel, the effect of any one of these upon the distribution of stray currents may most easily be studied in connection with the starting or shutting down of that particular source. When substations are operated only during part of the day, tests may be arranged to take advantage of this. When the substations are continually in operation, resort may be had to the method of simultaneously observing the load indicated by the station instruments, and the quantities to be measured on the structure being surveyed. Recording instruments are often useful for this purpose.

When the sources of power are not supplying the trolley in parallel but are confined to certain definite districts, a close study of the railway schedule should be made as it will frequently be possible to select some set of conditions where the current at points of observation must be coming almost wholly from one of the sources on account of the relative positions of cars, etc. Where two electric railways operate independently without connection between their trolleys but with intersections or junctions between their tracks, the situation is similar to that just described where the railway trolley is divided into insulated sections and the same methods of investigation can be followed. Where there is no connection between either trolleys or tracks of two independently operated electric railways this same method should also be followed, *i.e.*, of observing stray current conditions when one road is using considerable current in the immediate neighborhood and the other road is using little or none and comparing the observations with those obtained when both roads are using normal amounts of current in the neighborhood. It is to be noted that when two railways are without any electrical interconnections between either trolleys or tracks, the track return of either may carry stray current from the other railway and if the track return is of high conductivity it may assist materially in producing adverse electrolytic conditions on other earthed structures particularly in cases where it provides a short route between two points between which considerable potential difference exists.

The earth ammeter, previously referred to, may occasionally be found useful in checking up conditions indicated in the systematic survey observations. The construction of the device is described in the apparatus sections. If care is taken to have the plates placed perpendicular to the direction of current flow, the current density at the point of measurement may be indicated by the current flowing through the instrument. If necessary, the lines of current flow may be determined by voltage readings between test electrodes before burying the instrument.

The greatest care should be taken in placing the instrument to avoid unnecessary disturbance of the soil, in order that the flow lines may follow, as nearly as possible, their normal directions.

Whenever excavations or other exposures of pipe surfaces make it possible, measurements of the resistance of pipe joints should be made. Where the joints are of moderate resistance, that is, not so high as to prevent current flow upon the pipes, this measurement may be made by simultaneous observations of the fall of potential across the joint, and along a measured length of the pipe; the pipe joint resistance may then be expressed as equivalent length of pipe, or, by reference to tables, in ohms. These measurements are of importance in indicating the characteristics of the pipe line as an electrical conductor, in estimating the probability of corrosion at joints due to shunting, etc.

Wherever the surfaces of the earthed structures under investigation are exposed during the course of the tests, their conditions should be noted. The pitting of the metal surfaces or the presence upon them of rust or other oxidation products, or an obvious reduction in the thickness of the metal or any other evidence that corrosion has taken place, is not of itself direct evidence that electrolytic corrosion has occurred. Corrosion from any cause whatever would be expected to reduce the thickness of the metal, and the rate at which such corrosion occurred and its possibilities in the way of irregularity of attack on different portions of the surface, would determine the occurrence of pitting. Many of the products of corrosion which will be encountered can also be produced through purely chemical reactions, as well as by electrolysis. When the measurements made in the survey demonstrate that current is flowing from structure to the earth at the point where corrosion is observed, conclusions can be drawn as to the causative relation between the presence of stray current and the evidences of corrosion. Whatever the conditions found in the survey readings, the condition of obviously corroded metal surfaces should always be carefully noted, as it is, of course, always possible that at some past time stray current has been flowing from the surfaces to earth, or that some local condition has been favorable to the "self-corrosion" of the structure. Points where substantial corrosion of the structures under investigation is found, are always to be regarded as good locations for taking the samples of soil referred to in the following paragraph.

It is often desirable to gather data relative to the electrical and chemical characteristics of the soils in the area studied. As different types of soil are encountered in the course of the survey either in the making of excavations or through the observation of changes in surface conditions, samples should then be taken and their electrical conductivities determined. It is often desirable also to make chemical analysis of a number of samples of ground waters and of the water-soluble portion of soil samples secured for conductivity tests.

34. Application of Remedial Measures—Re-surveys. The survey methods described in the previous paragraphs include practically all of the work which would be done in an extensive original survey, that is, in a district where no work had been done previously. While this problem in all of its aspects has been investigated in only a few American communities, it will be found that more or less complete surveys have been made in almost any area traversed by electric railways.

The test methods described are not all of equal value for all problems; their application depends upon the particular problem under consideration. Further, many of the tests require considerable experience and technical skill in application, to avoid erroneous and misleading results. For these reasons, extensive surveys should only be undertaken by experienced investigators.

Following the completion of the original survey, a decision will be reached as to whether measures for mitigating electrolytic corrosion are necessary, and if so, what methods are to be applied. Conclusions as to the effectiveness of any protective measures should be based upon repetitions of the test made in the orginal survey. The amount of repetition necessary will depend upon the character of the protective measures adopted. Thus, general improvements in railway return circuits will ordinarily require a complete re-survey of the affected area. The installation of an insulating joint between the main line structure and a branch should, on the other hand, require little more than tests over short sections either side of the joint, to determine that the current flowing has been reduced and that no objectionable corrosive conditions have been introduced at the joint itself.

If railway return circuits are being changed, some observations of overall potentials and potential gradients will naturally be made during the course of reconstruction, to check the design upon which the work has been based. Observations should be made before installing drainage systems for cables, if necessary using available conductors temporarily to connect the cable sheath and the railway bus-bar or some other suitable point on the railway return, and the effect of drawing current from the cable system observed. The installation of such protective measures as insulating joints or insulating coverings should be carefully supervised as much depends upon the thoroughness with which the work is done.

In re-surveys after the installation of protective measures, the character of the underground structure will make it necessary to pay special attention to some particular class of observations. With piping systems and power distributing cable systems special attention should be given to the amount of stray current flowing on the structures, since a principal object of the remedial measures will have been a reduction in this current. When insulating joints have been installed tests of potential to earth from each side of the joint are required to make sure that the local flow of current to earth has not risen to an amount which will endanger the structure. Tests of stray current in the system on either side of the joint are also required to determine that the effect desired from its installation has been obtained.

When drainage connections are attached to cable systems, tests of potential to earth must be made throughout the area affected. The connection should make the cable negative to earth at all points, but only by slight amounts at or near the point of its attachment, as otherwise the cable will carry more stray current than is needed for its protection, and it becomes a source of danger to other undrained structures.

Where insulating joints or other protective measures are applied to structures buried in the earth, care should be taken to attach testing leads to be used in future surveys. Such connections will be of the same general type as the current measuring leads for pipes (See Fig. 1.).

Electrolysis surveys should be repeated at suitable intervals. In case the original survey did not disclose conditions requiring the application of remedial measures, it is still necessary to make sure that adverse conditions have not since arisen. Where protective measures have been applied, surveys are needed to make sure that the remedies remain effective and adequate. The interval between surveys will depend upon the importance of the structure and upon the time required to produce appreciable damage in case a substantial change in stray current conditions occurred. The results of all such surveys should always be compared with those of previous surveys to ascertain whether changes in stray current conditions are taking place. When any substantial changes or additions are made in the electric railway plant, surveys of the earthed structures liable to be affected by the new conditions should promptly be made.

B: APPARATUS.

In this section descriptions are given of the apparatus and tools which are essentially special for electrolysis work. The tools ordinarily used for handling wires and making good contacts in electrical work will also be needed but no special description or listing of them seems to be necessary in this place.

35. Portable Measuring Instruments. The portable measuring instruments required in electrolysis survey work include voltmeters, millivoltmeters and ammeters. Separate instruments of each kind can, of course, be carried but it will usually be found more convenient to employ the special portable instruments which have been designed particularly for this work.

Two such instruments which the Weston Electrical Instrument Company manufacture for this class of work are as follows:

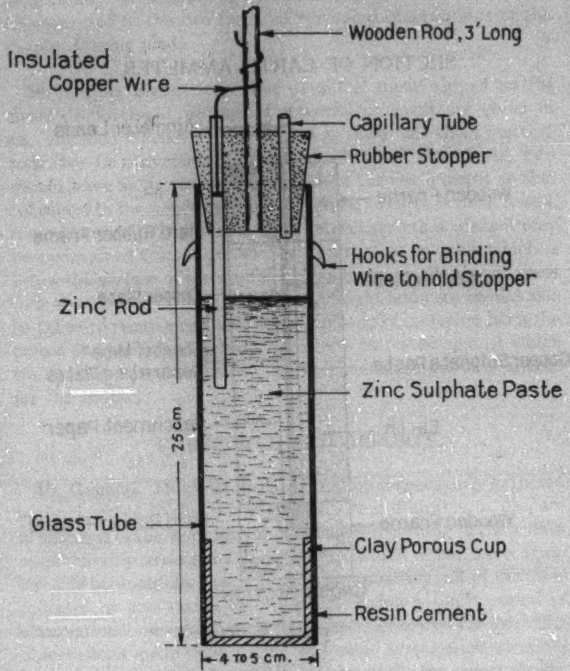
> Model 1, combination millivoltmeter and voltmeter, has its zero in the center of the scale and reads in both directions. Ranges of 5, 50 and 500 millivolts and of 5 and 50 volts are convenient. It is made with a specially high resistance of from 500 to 600 ohms per volt so that the 5 millivolt range has a resistance of about 3 ohms. These high resistances increase the accuracy of measurements and particularly minimize errors due to resistances of leads or contacts. Ordinary switchboard shunts provided with binding posts and adjusted for 50 millivolts may be used to make this instrument serve as an ammeter. Convenient ranges for these shunts in electrolysis work are, 5, 50 and 500 amperes.
>
> Model 56, combination volt-ammeter, has its zero in the center of the scale and reads in both directions. Ranges of 10, 50 and 500 millivolts, 5 and 50 volts and 100 amperes are convenient.

The center scale feature referred to in the description of these instruments is an important one in electrolysis work, as it is not always possible to determine in advance the direction of current or potential, and readings may also vary from positive to negative values during the making of observations at many testing points. When simultaneous readings have to be taken at two or more testing points it is important to use similar instruments at all points. If dissimilar instruments are used their periods of vibration may differ and with the fluctuating voltages and currents encountered in much of this work accurate simultaneous measurements cannot be made unless the instruments used have the same periods of vibration.

36. Recording Instruments. Recording measuring instruments are usually arranged to give 24-hour records without change of chart. By using a sensitive millivoltmeter in the recording instrument and providing it with a number of voltage ranges as well as with suitable shunts, a single instrument can be made available for taking all of the voltage and current readings required in electrolysis work. The original type of Bristol recording instruments make their records upon a smoked chart which has to be treated subsequently with a fixative supplied with the instrument in case it is desired to preserve the record. The Bristol instruments are regularly made with a clock supplied with a changing lever so that the disc can be made to rotate either in one hour or twenty-four hours. Both the Bristol Company and the Esterline Company have recording instruments which give an ink record on a paper strip. In either type of instrument center scale zeros should be called for so that variations between positive and negative values will be recorded on the chart.

37. Normal Electrode. The Haber normal electrode also called non-polarizable electrode consists of a rod of zinc which is enveloped in a wet paste of zinc sulphate contained in a glass tube which has had cemented to it at the bottom a porous clay cell. The other end of the tube is closed with a stopper from which the zinc rod is supported. an insulated wire is led from the end of the zinc rod through this stopper to the upper end of a wooden rod which also enters the stopper and serves for the purpose of handling the electrode. A capillary tube is also run through the stopper in order to have the interior of the tube at normal atmospheric pressure. The zinc sulphate paste is made by adding saturated zinc sulphate solution to fine zinc sulphate crystals until the mixture has attained a semi-fluid condition. A sketch showing details of construction for this device is shown on the opposite page. (See Fig. 2.)

38. Earth Ammeter. The Haber earth ammeter consists of two thin copper sheets laid one upon the other with a thin sheet of mica or other non-absorbent insulating material between them. These two plates are gripped in a hard rubber rim which forms part of a square wooden frame. A paste made by mixing powdered copper sulphate crystals with a 20% aqueous solution of sulphuric acid is spread over the exterior surfaces of each of the two sheets of copper, the paste being enclosed on each exterior surface by a covering of parchment paper or some similar tough permeable membrane. Insulated wire leads of suitable length are run from each plate through the frame to connect with the measuring instrument. The opening in the frame may conveniently be square. Four inches is a convenient dimension for the sides of this square opening as this will yield an area of one-ninth of a square foot which is approximately equivalent to a square decimeter. The detailed construction of the instrument is shown in an attached sketch. (See Fig. 3.) When using the instrument, the spaces between the parchment paper and the outer edges of the wooden frame are first filled with


SECTION OF NON-POLARIZABLE ELECTRODE

Wooden Rod, 3' Long
Insulated Copper Wire
Capillary Tube
Rubber Stopper
Hooks for Binding Wire to hold Stopper
Zinc Rod
Zinc Sulphate Paste
25 cm
Glass Tube
Clay Porous Cup
Resin Cement
4 TO 5 cm.

CROSS SECTION
Figure 2

SECTION OF EARTH AMMETER

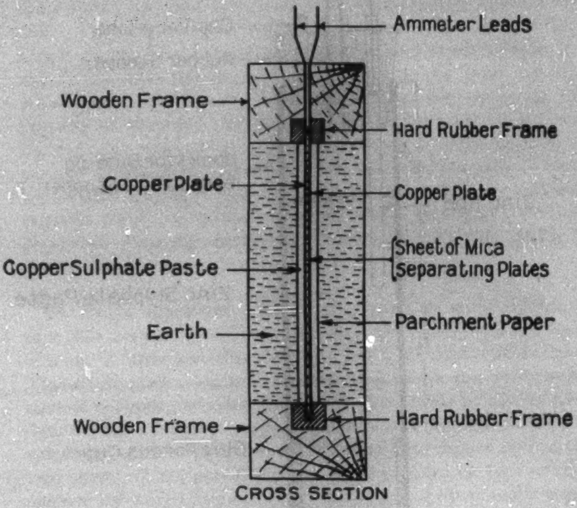

Ammeter Leads
Wooden Frame
Hard Rubber Frame
Copper Plate
Copper Plate
Sheet of Mica Separating Plates
Copper Sulphate Paste
Earth
Parchment Paper
Wooden Frame
Hard Rubber Frame
CROSS SECTION

Figure 3

closely packed soil taken from the spot where it is intended to make the measurement and the frame is then placed in a position perpendicular to the flow of current which it is desired to measure and completely buried in earth removed in the course of making the excavation to reach the structure whose condition is to be determined. A suitable low resistance milliammeter can then be connected to the two terminal wires and observations of the current flowing made.

39. Testing Electrodes. The details of metal tipped testing electrodes for use in readings of potential to earth are given in an attached sketch. (See Fig. 4.) Two of these testing rods may be conveniently carried at all times; one of the two should have as its testing tip a piece of the same metal as that contained in the structure whose potential to earth is to be tested, the other should be provided with a steel tip so that contact may be maintained from a distance with any pipe or cable which is below the surface of the ground. The metal on the tips of these rods should always be kept clean and bright and care should also be taken to remove rust and other products of corrosion from the points on the surface of the structure to be tested against which the steel tip presses so that a clean, bright surface will be available for the contact.

C: RECORDS AND REPORTS.

40. General. Much detailed information is necessarily gathered in the course of an electrolysis survey. It is desirable to prepare in advance of the work for the convenient recording of these data upon suitably arranged testing sheets, which either have upon one line or upon one sheet, as may be necessary, all of the data collected at any stated testing point during a single period of observation. Several typical data sheets prepared for recording observations made upon piping and cable systems are attached hereto as suggestive of possible arrangements for report sheets. The data thus collected can usually be best aranged for study if they are transferred to a map showing the system or systems included in the tests, and indicated thereon either in numerical form or through some graphical representation. It is desirable to indicate positive and negative relations by making records on the maps in different colors.

Apart from the data obtained through observations in the

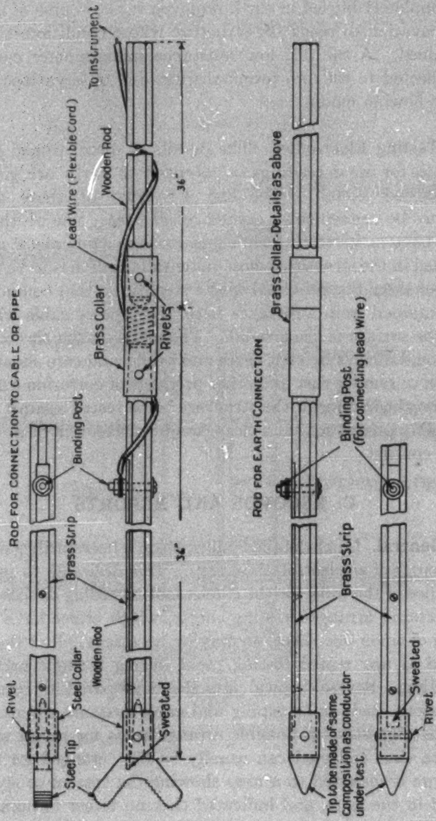

ROD FOR CONNECTION TO CABLE OR PIPE
To Instrument
Lead Wire (Flexible Cord)
Wooden Rod
36"
Brass Collar
Rivets
Binding Post
Brass Strip
Wooden Rod
36"
Steel Collar
Rivet
Sweated
Steel Tip
ROD FOR EARTH CONNECTION
Brass Collar-Details as above
Binding Post (for connecting lead wire)
Brass Strip
Sweated
Rivet
Tip to be made of same composition as conductor under test.

Figure 4

work of the electrolysis survey it will be seen that the records obtained relating to the systems under observation should include the following:

41. Electric Railways.

1. Maps showing locations of sources of power supply, tracks, and negative feeders and other connections between bus-bar and track. Also locations of positive feeding connections to trolley and of all section insulators in trolley.
2. Information as to size of rails, methods of bonding and standards of bond maintenance.
3. Information as to any direct ground connections applied to the railway return system, and any special track features which may affect the flow of stray currents.

42. Piping Systems.

1. Maps showing all main piping lines and branches (except building connections) and sources of water, gas, etc., from which the piping systems are supplied.
2. Information as to sizes of pipes and metals of which they are composed, and details of the standard methods of joining main and branch line pipe sections.
3. Information as to method of joining building connections to main supply pipes including metals used for the building connection pipes and the depth to which such connections are buried.
4. Location and description of any protective devices such as insulating joints or drainage connections which may have been made a part of the piping system.
5. Information as to methods of attachment and construction employed in carrying pipes over highway or railway bridges or under water courses, swamps, etc.

43. Cable Systems.

1. Maps showing locations of all subway and conduit routes and giving number and sizes of cables in place therein or the total cross-section of lead sheaths expressed in equivalent copper, also locations of power stations, sub-stations or other centers from which cables radiate.
2. Locations, route and sizes of all drainage connections attached to cable systems, also locations of all insulating joints in cable systems, of any jumpers which may be run to establish a metallic circuit across an insulated gap in the cable system and of any conductors run to reinforce the carrying capacity of the cable system for stray currents.
3. Information as to methods of attachment and construction employed in carrying cables over highway or railway bridges or under water courses, swamps, etc.

44. Bridges and Buildings.

1. Locations of structures with respect to electric railways.
2. Information as to methods of construction employed in carrying electric railway, pipes and cables across bridges and particularly as to whether any of these other structural systems make electrical contact with the metal structure of the bridge.

45. General Conditions.

1. Maps showing locations of water courses, swamps and other features tending to produce locally earth of high unit conductivity.
2. Records of electrical resistance of soil samples representative of the area.
3. Records of experience obtained in the use of different metals for pipes, etc., in the soils of the area.

It is desirable that in the preparation of records and of reports, consideration be given to the necessity of their perpetuation. All records which will be of permanent value in connection with the continued study of electrolysis conditions within the area which will be necessary in order to make sure that injurious changes in conditions do not occur, should be prepared in a permanent form capable of withstanding considerable handling.

III. AMERICAN PRACTICE.

There is no standard practice in the treatment of electrolysis problems in America. In many localities the existence of such a problem is scarcely recognized; in others the problem has been given much study, and mitigating systems widely varying in character have been installed.

Much of the information made available to the committee is contained in confidential reports to which it is not possible to make reference, because electrolysis is the subject of controversy between conflicting interests. Unfortunately, also it is impossible in some cases even to refer to places where particular expedients have been employed, or to state either the extent or the results of such use. It has, therefore, been necessary in most instances to make statements of what is the practice, without citing the authority or naming the places where such practice may be found. In compiling this report, therefore, the committee has been influenced most largely by those instances of practice within its knowledge where the greatest amount of study has been given to the subject, and where the results obtained seem best to justify its use. The committee has embodied in this report only matters of fact for which it has authority.

A. MEASURES APPLIED TO RAILWAYS.

46. Insulation. Under this sub-heading have been considered three general measures, namely: *a. Complete Insulation*, which does not involve the use of the running rails as a portion of the electric circuit, *b. Substantial Insulation*, which does involve the use of the running rails as a portion of the circuit, but, due to the type of construction employed, to a very large extent prevents stray currents, and *c. Partial Insulation*, which comprises using such means as are available to insulate the running rails of ordinary street railways in so far as practicable.

(a) Complete Insulation. Instead of using the running tracks as part of the return circuit, a separate insulated return conductor is employed for this purpose. In this case the entire electric circuit of the railway system is insulated from ground, and, there being no voltage drop in contact with earth, stray currents are entirely prevented. Complete insulation of the railway circuit is accomplished in the double underground conduit trolley system, by employing insulated positive and negative conductors in underground conduits. This system is in use on the surface lines on Manhattan Island and in portions of Washington, D. C. This is also accomplished in the double overhead trolley system by employing separate positive and negative overhead trolley wires insulated from ground; many years ago examples of this system were installed in Washington, D. C., and Cincinnati, Ohio. The practice while effective in this respect and in use for a long term of years has not spread to other cities possibly because of the unsightly appearance of the overhead structures due to the multiplicity of wires and because of the increase in operating difficulty and expense which it entailed.

(b) Substantial Insulation. Interurban and electrified steam roads generally require the rails to be supported on wooden ties set in well drained broken stone or gravel ballast. The insulation afforded by such construction practically removes danger from electrolysis. Leakage is in some instances found to be as low as .00016 ampere per rail per tie under dry weather conditions, increasing to .0055 ampere when wet with 10 volts between the rail and ground. On steel structures where the ties are only partially in contact with ground and the ties cannot become waterlogged, this leakage is even less. The substantial insulation of a ballasted roadbed has, in some installations, been rendered ineffective by bare negative cables in damp earth or by metallic connections between the tracks and steel supporting construction. Conditions are found to be very favorable for rail insulation where the tracks are in subways or under cover protected from the weather, permitting the ballast and ties to become permanently dry.

(c) Partial Insulation. The escape of current from tracks largely buried is decreased by high contact resistances between the tracks and the surrounding medium. The total resistance to flow of escaping current is found to vary with the earth resistance and the contact resistance between earth and rail. Since the earth resistance is usually low, the contact resistance is generally found to be the controlling factor in the leakage path; hence, partial insulation is found effective in reducing leakage with the low voltages commonly encountered. On a grounded trolley system in city streets it has been found beneficial to have the rails as nearly enclosed with insulating material as possible.

47. Reduction of Track Voltage Drop.

(a) **Bonding.** The best types of solid rail joints in actual use give the same electrical conductivity at the joint as in any other part of the rail length. The standard of good practice in some electrified steam roads is that, the resistance through the rail joint shall be equivalent to that of a 20-inch length of the rail adjacent, and should the resistance exceed 42 inches, that the bond should be remade. With respect to the practice of bonding in street railway systems, it may be said that there is no standard equivalent length of rail to cover all conditions, but each railway company establishes its own standard, depending on local conditions. The equivalent resistance of the rail joint in terms of length of rail will depend on the length and size of the bond, the terminal contact resistance and the conductivity of the rail. In large cities bonding to an equivalent resistance of from three to six feet of rail is common practice. In suburban districts higher bond resistances are often used. The equivalent resistance of rail joint which is adopted by different railroads necessarily varies widely with the condition of load and class of bond employed. The class of bond chosen is in many cases determined by mechanical conditions, such as the foundation upon which the track is laid.

Bonds are generally classified according to the method of fastening them to the rail. *Soldered bonds* are soldered to the head, base or web of the rail. *Pin expanded bonds* have holes drilled in their terminals, through which a steel pin is driven to expand the terminal into a hole drilled in the rail. After expansion a steel cylindrical plug is driven in the expanded hole to prevent contraction. *Brazed or welded bonds* are attached to the rail by heat generated electrically or by an oxy-acetylene flame applied to the terminal of the bond. *Compressed terminal bonds* and *compressed multiple terminal bonds* have their terminals formed into a solid cylindrical stud, or studs, and are compressed in the rail holes with screw or hydraulic compressors or by hammer blows, which expand the studs in threaded or beaded holes of the rail. A special type of this bond has large contact surfaces about the terminal, so that the bonds can be soldered and compressed to the rail.

The carrying capacity of bonds has sometimes been found insufficient to keep their temperature within safe limits under conditions of maximum load where bonds involving soldered joints are used. The resistance of a rail joint is found to be affected largely by the contact resistance between the bond terminals and the rail. Good contact and large surface of contact at the bond terminals are found necessary to low joint resistance. Replacement of bonds is generally made necessary by depreciation at the contacts, the breaking of strands by vibration or by mechanical injury.

There are now in general use several different types of rail joints which render additional bonding unnecessary. Among these types of rail joints are the following: *Cast Welded*: The rails are connected together by pouring molten iron into a mold that surrounds the joint, and when the metal cools the joint is rigid and of low electrical resistance. Thermit welding is another example of this method, the iron being liberated at a white heat from a mixture of iron oxide and aluminum which is ignited in a crucible. *Electrically Welded*: Iron splice plates are electrically welded to the rail. *Nichols Zinc Joints*: This joint is made by pouring molten zinc between the fish plates and the rail ends. The zinc is poured in after the fish plates are bolted on, and the expansion of the zinc in solidifying is relied upon to make a contact between the fish plates and rail ends which is reported to be permanent. *Romapac Continuous Rail*: The rail consists of two pieces which are so laid that the rail head joint and the rail base joint are staggered, then the rail head is rolled or crimped on to the rail base thus forming a continuous electrical path.

(b) **Cross-bonds** are electrical conductors for equalizing the current flow in the rails. When the roadbed is dry they are usually installed bare in the ground. Insulated cable is, however, sometimes used, and the insulation is protected by a heavy braid or circular loom tubing.

The important objects of cross-bonding are to equalize the current flow between rails and to insure continuity of the return circuit in case of a broken rail or bond in any one rail. It is usual practice on suburban railways to place cross-bonds at intervals of 1,000 to 2,000 feet and at shorter spacing, sometimes as low as 300 feet on street railways. Cross-bonding between parallel tracks is in some cases installed with the same frequency as between the rails of the single track; in other cases at less frequent intervals.

In determining the location of cross-bonds in connection with alternating current single track signal circuits, a departure from ideal spacing becomes necessary, owing to the fact that cross-bonds are permissible only at the reactance bonds. The signal reactance bonds are located between the signal block sections, and these sections are more or less fixed for train operating conditions. The general method used under these conditions is to cross-bond at all signal reactance bonds and install additional cross-bonds with reactance bonds at intermediate locations to obtain the most satisfactory resistance conditions in the sections fixed by the signal system.

The common practice of electrified steam railroads is to use cross-bonds with a conductance equal to one track rail, or about 1,000,000 circular mils. Street and interurban railways employ copper having a cross-section of from 200,000 to 500,000 circular mils.

Some companies provide jumpers at switches, frogs and at other special track work, to insure that the electrical continuity of the bonded rail will be maintained. This is usually accomplished by jumpers extending around the special work, except where broken rail signal protection is required, and in such cases the frogs are bonded in the return current system. In recent practice these jumpers are made of insulated copper cables, except in dry locations, as, for instance, in permanently dry rock ballast, or on elevated structures with wooden ties and no ballast, the cables being kept clear of the steel structure. The electrical leakage from a bare negative jumper in damp earth has been known to offset the effect of many miles of most careful track insulation. Under such conditions the bond is gradually destroyed by electrolysis.

(c) **Conductivity and Composition of Rails.** The conductivity of the track rails used by several interurban and electrified steam railroads has been found to be equivalent to about 1/12 that of copper, and this figure generally holds approximately true for girder types of rails, except when alloy steel is used, in which case higher resistances are found. The track rails are specified for their mechanical qualities, and, where these interfere with the electrical requirements, it is customary to give the mechanical qualities preference. The composition of rails for heavy service used by one of the large electrified steam railroads, in percentages, is as follows:

Carbon	0.62 to 0.75
Manganese	0.70 to 1.00
Silicon	0.10 to 0.20
Phosphorus	not to exceed 0.04

The American Electric Railway Engineering Association has adopted the following standard composition for heavy service rails:

	Class A Rails	Class B Rails
Carbon	0.60 to 0.75	0.70 to 0.85
Manganese	0.60 to 0.90	0.60 to 0.90
Silicon	Not more than 0.20	Not more than 0.20
Phosphorus	Not more than 0.04	Not more than 0.04

d. Reinforcement of Rail Conductivity. Early track construction practice in this country often included bare wire laid between the rails and connected to each bond. Sometimes one such wire was used for each rail; sometimes one for each track, and sometimes one served for a double track. The wires varied from No. 4 to No. 1, and were either of copper or galvanized iron. Their conductivity was small and they were subject to electrolytic injury and frequent breakage. This construction has practically gone out of use. It is, however, common to find the rails supplemented in the vicinity of supply stations by large conductors connected in parallel to the rails. This is not infrequently done by the use of bare copper wire or cable buried between rails, and hence in full contact with the earth. Old rails, bolted and bonded together and buried beneath or beside the track, have also been used in some cases.

Buried bare conductors, however, increase the contact area between the return circuit and the earth, and the tendency to augment stray currents thus caused off sets, to a greater or lesser extent, the benefits attained by the reduction of drop. The benefits to be derived, therefore, from an electrolysis standpoint, may, if use is made of bare conductors buried in the earth, be open to question. The direct benefits that accrue from the practice of reinforcing the conductivity of the rail, listed in what may be considered their order of importance, are: (1) Reduction of energy losses; (2) The maintenance of a higher average voltage at the cars, especially at times of peak load, thus resulting in improved car service and car lighting; and (3) The reduction in potential drop in the rails, thus reducing stray currents and, in turn, therefore, lessening the damage to the extent that these stray currents are reduced, qualified, however, in accordance with the statement previously made if buried bare conductors are used.

Where conductors paralleling the rails are installed as an electrolysis mitigation measure, they are usually insulated from earth by carrying them overhead or in underground conduit. The practice varies as to the method of connecting such conductors to the rail; they are sometimes connected at the ends only but more generally at intermediate points also. Where this arrangement is used the track rails are connected to the negative bus at the nearest convenient point.

Conductors are here regarded as in parallel with the rails when one end is connected to the track and the other to a station bus-bar which is connected directly to the rail by a conductor of negligible resistance. The use of such conductors should not be confused with the "Insulated Track Feeder System," which has for its prime object the mitigation of electrolysis. This is treated under a subsequent heading.

(e.) **Use of Additional Power Supply Stations and Distribution of Load.** The growth of electric railway systems in large cities has often led to the installation of additional power stations or substations for the more economical and satisfactory operation of the railroad. This has also reduced the track voltage drop and subdivided the areas over which leakage from rail to earth occurs and thus has had the effect of reducing the stray currents.

The effect of providing additional centers of power supply can best be illustrated by the curves on Figure 5, which, while deduced from theory, illustrate in a simple case effects such as have been observed in practice.

The curve *SAO* of Figure 5 represents the track voltage

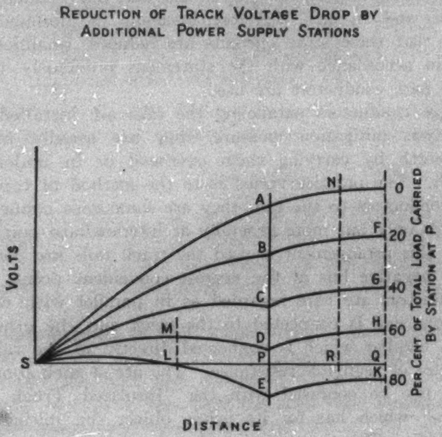

REDUCTION OF TRACK VOLTAGE DROP BY
ADDITIONAL POWER SUPPLY STATIONS
VOLTS
N
A
0
F
B
20
G
C
40
M
H
D
60
S
L
P
R
Q
K
E
80
PER CENT OF TOTAL LOAD CARRIED
BY STATION AT P
DISTANCE

Figure 5

drop on a portion of an electric railway system having a uniformly distributed load. This curve is a parabola with a vertical axis and with the apex at *O*—that is, at the end of the line.

The curve *SBF* illustrates the condition of a substation located at *P* (33 per cent of the distance from *Q* to *S*) carrying 20 per cent of the total load. In this curve the portion *BF* is identical with *AO*. As the load is uniformly distributed, 33 per cent of the load is on the portion of the line shown by *PQ*, and of this 33 per cent, 20 per cent is carried by the substation *P*. The remainder, or 13 per cent, is carried by the station *S*. The point *B* on the curve *SBF*, therefore, corresponds to the point *N* on the curve *SAO*, the distance *QR* being 13 per cent of *QS*.

In the same manner the curves *SCG*, *SDH* and *SEK* are drawn showing the conditions when the station *P* carries 40 per cent, 60 per cent and 80 per cent, respectively, of the total load. The summit of the curve *SMD*, in which the station *P* carries 60 per cent of the load, is located so that *PL* equals 60 per cent minus 33 per cent, or 27 per cent of the total length *SQ* to the left of *P*. The distance *QL* is, therefore, 60 per cent of the total length *QS*.

In general, the conditions are more complicated than those here assumed, and will ordinarily prevent an accurate determination of the relative location of the negative busses of the two stations. It is possible, however, to make tests which will verify each of the points which have been used in preparing the curves, although it may not be possible to verify all of them at any one test or in one location.

48. Three-wire Systems. As far back as 1894, and possibly earlier, consideration was given to a three-wire system of operation for electric street railways, wherein the tracks acted as the neutral circuit. The reason for considering such a system was to reduce stray currents through the earth. Installations of this sort were tried out in Pittsburgh, Pa., Lowell, Mass., Portland, Ore., and Seattle, Wash., in the earlier days; somewhat later an experimental installation was made in Cambridge, Mass. In the *Transactions* of the American Institute of Electrical Engineers for 1907, Vol. XXVI, No. 1, pages 268 to 280, Messrs. Paul Winsor and J. W. Corning report the results of an investigation to determine the feasibility of using the three wire system for the purpose of reducing stray currents through the earth. This investigation showed that the three-wire system of operation materially reduced the track voltage drop, and therefore reduced the amount of stray current in the earth and in underground metallic structures. The figures and curves shown by Mr. Corning indicate that there is a reduction in current flowing on pipe lines tested by him of the order of nearly 90 per cent.

Until very recently it was thought that three-wire systems contained certain serious inherent disadvantages. It was felt that the complications in machinery, difficulties in successfully insulating trolleys of different polarities, difficulties in equalizing the load between different sections, and, further, the necessity for the installation of larger generating units to compensate for the difficulties in balancing than were required with the single-trolley grounded system, were so great as to preclude the consideration of the three-wire system for electrolysis mitigating purposes. Recently, however, interest in this system has been renewed, and at least some of the difficulties successfully overcome, with the result that at the present time there are in operation or being installed two sectionalized three-wire systems—one in operation in the Hollywood district of Los Angeles, Cal., and the other in process of installation in West Springfield, Mass. It is known that the three-wire system has been in operation for some twelve years in Nürnberg, Germany, and for a considerable length of time in Brisbane, Australia.

The three-wire system may take two different forms, which, though the same in principle, differ decidedly as to the arrangement of the feeders. In one form, known as the *Parallel Three-wire System*, one trolley of a double track road is negative and the other positive, the tracks being neutral. In the other form, known as the *Sectionalized Three-wire System*, the feeding district is divided into sections and alternate sections are supplied by feeders running directly from the positive bus, while the remaining sections are supplied by feeders from the negative bus. For a more detailed description of these two forms of three-wire systems reference is made to the Bureau of Standards' Technologic Paper No. 52.

49. Reversed Polarity of Trolley System. With the ordinary construction of electric railways using the running tracks as a part of the electric circuit, the overhead trolley wire or third rail is made the positive conductor, and the running tracks the negative or return conductor, only one exception to this rule being known to the Committee. With the usual arrangement stray currents escape from the running rails into ground and flow to underground structures at points distant from the power station, and such escape of stray currents from the rails generally takes place from a large area of outlying lines. The current then returns to the tracks from ground and from underground structures in the neighborhood of the power station. For this reason the most acute danger from electrolysis is usually produced on underground structures in the neighborhood of the power station.

To reverse this arrangement of polarity and make the rails the positive conductor, causes current to leave the structures over widely scattered areas, so that the current density leaving the underground structures will be so small as to prevent acute danger from electrolysis. This arrangement is being used in New Haven, Conn. at the present time. It is found, in this instance, that all potentials and currents which formerly existed when the rails were the negative conductor have now reversed in direction, but have the same magnitude. It is also found that current leaves underground structures over a widely scattered outlying area. This arrangement has not been in operation a sufficiently long time to determine whether or not the danger from electrolysis at any one outlying point will become acute. The reversal of polarity renders extremely difficult the effective drainage of underground structures, because there is no definite point of minimum potential to which to drain.

50. Booster System. Negative boosters have, in the past, been employed in connection with drainage systems, and are in use in connection with the insulated track feeder system abroad, but not in this country, so far as known. The use of negative boosters is simply a means of caring for voltage drop other than by the use of copper. Boosters have proved economical under certain conditions, and uneconomical under others. In general it is simply a question of the fixed charges on copper as against the fixed charges and operating cost of machines. In one instance where a booster was employed in connection with a drainage system it was discontinued, not because the addition of a booster to a drainage system was unsatisfactory, but because the drainage system itself did not adequately care for the trouble. Various special arrangements involving the use of boosters in electrolysis mitigation have been proposed, but in so far as is known they have never been placed in successful operation.

51. Interconnection of Railway Return Circuits. Wherever two or more electric railway tracks come close together, whether they belong to the same railway system or to different railway systems, large differences of potential between them, with resultant high potential gradients through ground, are often found to occur unless the tracks are electrically connected. Interconnection of tracks has been found to be of particular advantage where two or more lines of electric railway, operating in one locality and belonging to the same or to different systems, are supplied from two or more power stations located in different parts of the city. By interconnecting the tracks of such lines in the neighborhood of the power stations, and also at several intermediate points, an interchange of current has been brought about, whereby the drop formerly existing in one track has been balanced by the drop in the opposite direction in the other track, the rail drop in each track greatly reduced, and all high potential gradients between the tracks eliminated. This reduction in rail drop resulted also in a corresponding reduction of losses.

52. Use of Alternating Currents. When the first alternating current railways were proposed, the question of possible electrolytic effects received special investigation. Considerable work was done upon a laboratory scale, in which it was established that alternating currents could produce corrosion on electrodes of the metals commonly used underground, such as lead and iron, but that the effects were very much less in magnitude than those produced by equivalent quantities of direct current, usually less than one per cent and in most cases negligible.

It has not as yet been possible to determine whether these effects, demonstrated in an experimental manner, are being reproduced in the case of actual installations. In the case of practically all actual exposures which have occurred up to the present time it has been impossible to dissociate effects which might be due to an alternating current exposure from the effects which are due to a simultaneous exposure to stray currents from direct current railways. Whether alternating current corrosion is proceeding at the relatively slow rate indicated by the experimental investigations and will at some time produce damage to subsurface structures, cannot now be determined. Special measures for the reduction of leakage of current to earth are being tried out in one alternating current railway, but neither the construction nor the results have yet been made public. (See Bureau of Standards Technologic Paper No. 72.)

53. Insulated Track Feeder System. The insulated track feeder system or the insulated return feeder system is employed in a number of American cities at the present time, and plans are being made looking to its installation in a number of other cities.

The arrangement of feeders described under this title is not generally understood, and as it is commonly confused with the reinforcement of track conductivity, the following explanation is therefore made.

Stray current which is the cause of electrolytic corrosion is traceable directly to voltage drop in the rails. With a given resistance between rails and earth any means which will most effectively reduce this voltage drop is, therefore, the means which will most effectively reduce electrolytic corrosion. The reinforcement of the conductivity of the rails by paralleling them with other conductors operates definitely in this direction, provided the paralleling conductors are not themselves in contact with the earth. When, however, it is desired to reduce the voltage drop to such a point as will insure reasonable immunity from electrolytic troubles, the employment of copper in parallel with the rails generally proves prohibitively expensive. For example, an average grade of rail has a resistance 12½ times that of copper of the same cross-section. Its conductivity is therefore approximately the equivalent of 10,000 c. m. of copper per pound per yard. Such a rail weighing 100 pounds per yard would be approximately equivalent to a 1,000,000 c. m. cable. To reduce the track voltage drop to one-half its former value, where such a rail is employed, would require a 1,000,000 c. m. cable laid parallel to each rail of the track for its entire length. This large investment in copper would reduce the losses of track transmission by but one-half, and would reduce the stray current by one-half. If bare copper in contact with the earth were used the stray current would be reduced by somewhat less than one-half. Thus, the practice to install return copper to reduce track drop with a grounded bus-bar is either prohibitively expensive or ineffective. It was because of these recognized difficulties that the *Insulated Track Feeder System* was introduced.

The insulated track feeder system employed in the American cities above referred to has the following distinguishing characteristics:

(a) The negative bus is insulated—that is, not connected to earth nor directly to the rails at or near the power or sub-station, except that, in some instances, it is connected to the rails through resistances sufficient in magnitude to insure that this point is at approximately the same potential as other track feeder points.

(b) The current is returned to the negative bus by insulated feeders leading from selected points on the track network.

(c) These feeders are connected to the track at their extremities only, or, if connected at intermediate points, are connected through resistances of such magnitude as to keep all connected points at approximately the same potential with respect to the bus.

The *Insulated Track Feeder System* is thus an arrangement having for its prime object the reduction of stray current through the earth. The insulated feeders are installed either overhead or in underground ducts, and extend from the negative bus to such points on the track network as have been determined, by either observation or computation, to be those from which the removal of current will prevent excessive track voltage drop. The negative bus is connected to the rails at the power house only through a resistance sufficient in magnitude to insure that this point is at approximately the same potential as other feeder connection points. When all feeder connection points are at the same potential the maximum effectiveness of the system as a means of reducing stray currents is found. The attainment of this condition requires track bonding of a reasonably high order of uniformity.

In most cases feeder connection points are not brought to the same potential, but a certain drop is allowed in the direction of the power station.

The insulated track feeder system is the equivalent of having the negative bus-bar of the power supply station divided into branches corresponding in number to the number of track feeder points, and distributed geographically over a considerable portion of the track network. This reduces both maximum and average current in the rails and also reverses the direction of the current in the rails on one side of each feeder point. These changes in the rail current directly reduce track voltage drop. The area from which current leaks to earth and to underground structures, and also the area from which current returns from underground structures and earth to the rails are subdivided. The combined effect of these factors is a substantial improvement in electrolysis conditions of underground structures. (See G. I. Rhodes, Trans. A. I. E. E., 1907.)

The efficacy of this system in reducing stray current is practically independent of the weight of copper in the individual feeders—that is to say, the voltage drop in the feeders may be either large or small, without material effect upon the stray currents.

As was pointed out under a prior sub-heading, negative boosters may be used with this system. The principles underlying the insulated track feeder system are the same, whether or not negative boosters are used.

B. MEASURES APPLIED TO AFFECTED STRUCTURES.

54. Insulating Joints in Large and Small Iron Pipes and in Lead-sheathed Cables. In a number of installations flow of stray current on metallic pipe lines has been prevented by the use of a sufficient number of insulating joints. It is found that where a pipe line is laid with every joint an insulating joint, the line has such a high electrical resistance that no measurable current flows on the line, although considerable potential gradient exists in earth parallel to the pipe line. In some installations it has been found sufficient to use comparatively few insulating joints to break up the electrical continuity of a pipe line and protect the line from electrolysis, but in these cases it was necessary to make adequate tests to assure that sufficient current did not shunt through earth around the joint to damage the pipe on the positive side of the joint. In these installations it has been found necessary to install such insulating joints, not only in the positive areas, but also in the negative areas in all places where considerable potential gradient in earth parallel to the pipe existed. It is found, in fact, that the frequency with which insulating joints must be installed in a pipe line in order to assure reasonable protection from electrolysis, depends upon the potential gradient through the earth and upon the electrical resistivity of the earth in the neighborhood of the pipe line.

Tests on joints buried in earth have shown that the resistance of a short insulating joint is practically the same as that of a long joint, but that a long insulating joint gives a more even distribution of leakage current than a short joint, and that, therefore, a long insulating joint is to be preferred where there is considerable potential difference across the joint or where the resistivity of the surrounding soil is very low. It has also been found that the effect of a long joint can be secured from a short insulating joint by surrounding the joint and the pipe for some distance on each side of the joint with a heavy layer of insulating material. In a number of installations of such insulating joints in important pipe lines, each joint and the pipe for a distance of from 5 to 25 feet on each side of the joint have been surrounded by a wooden box leaving a space of from 1 to 2 inches between the outside of the pipe and the inside of the box, and the space then filled with pitch, parolite, or similar material. In this way an insulating joint having an effective length of from 10 to 50 feet was secured. (See also Bureau of Standards Technologic Paper No. 52).

In a large number of cases small service pipes have been damaged by electrolysis from stray current leaving the service pipes for earth, which current was found to flow to the service pipes either from the main or from house piping. In the latter case the current was found to reach the house piping by way of a service pipe from another piping system. In some cases of this kind such current flow to service pipes has been greatly reduced or prevented and the service pipe thereby protected from electrolysis, by placing an insulating joint in the service pipe at the main or in the building, as the case may be.

In some cases it was however found necessary to install an insulating joint in the service at the main and a second joint in the building, the necessary locations of the joints being determined from the results of electrical measurements. This method of protecting pipes has been applied to isolated cases which were specially studied, but has not been generally applied to a large complicated city system of mains and services.

For wrought-iron or steel pipes of small and moderate size, various commercial insulating joints have been largely used. For large sizes of pipe a flanged type of insulating joint has been commonly used. This insulating joint has been made up by placing a disc of insulating material between the surfaces of the flanges, by placing insulating tubes over the bolts, and by placing insulating washers under the bolt heads and nuts. Red fibre has been most commonly used for the insulating material, except that for water pipes in some cases soft sheet rubber has been used for the packing between the flanges. Where such flanged insulating joints have been used in cast-iron mains the flanges have generally been cast as part of the pipe.

For water mains various forms of insulating joints employing white pine wood for the insulating material have also been used to a considerable extent. For cast-iron water mains with bell and spigot joints, these joints have in some installations been rendered insulating by placing a short wooden ring between the inside of the bell and the end of the spigot to prevent metallic contact between the pipe lengths, and then calking the joint with wooden staves of clear white pine shaped to fit the curvature of the pipe. In these cases the spigot end of the pipe was either cast without a bead or the bead was removed. The leaks that developed in the joint were stopped with white pine wedges. These simple joints have been found satisfactory for pressure up to about 75 pounds per square inch (5.27 kg. per sq. cm.) Where with higher pressures leakage developed through the pores of the wood, this was overcome by dipping the inner ends of the staves in red lead. The staves have also been reinforced in some cases by an iron band clamped around the spigot end of the pipe.

It is found that cement joints in cast iron pipes as ordinarily made have a very high resistance between adjoining lengths of pipe and that such joints may properly be classed as insulating joints. When pipe lines are laid with every joint, or even every other joint made of cement, the resistance of the pipe line becomes so great that the current flowing on the pipes will be greatly reduced. In practice, however, for mechanical reasons it has been found that cement or other insulating joints cannot be used under all conditions or for all sizes of pipe. In such cases, the entire drop of potential of the pipe line is distributed more or less uniformly over all of the cement joints and the drop in potential around any one joint is too small to cause any injury through leakage of current around individual joints unless the soil is of great conductivity.

This, however, will not prevent electrolytic corrosion in localities where current can reach the pipe by way of laterals, or when it is closely adjacent to other conducting structures which nullify the effect of the joints, or when there is leakage from another transverse pipe.

Insulating joints in lead sheaths of underground cables are in use to some extent, but they are not found to afford an effective primary means of preventing electrolysis. In some installations such insulating joints have been used in positive areas for the purpose of breaking up the electrical continuity of the lead cable sheathing and stopping rapid localized destruction from electrolysis, but such joints have not generally been found to afford permanent and complete protection. In certain special cases in practice insulating joints have been used in the lead sheaths of certain cables for the purpose of preventing current from reaching the remainder of a cable system. Common examples of this are found where laterals or services from a cable system pick up considerable current from an iron conduit or from pipes with which the cable or iron conduit may be in accidental metallic contact, which current is then delivered to the cable system. Such current flow to the cable system has frequently been effectively stopped by introducing an insulating joint in the lead sheath of the lateral or service where it leaves the iron conduit and before it is connected to the main cable system.

Particular points on main cable runs have also been found where considerable current was picked up. Such cases have frequently arisen where a cable crosses a bridge in an iron conduit, and where the conduit is in metallic contact through the structure of the bridge with trolley tracks on the bridge, whereby large currents were found to flow from the tracks through the bridge structure and iron conduit to the cable system. In such cases insulating joints have been installed on each side of such sections or crossings so as to interrupt the metallic continuity of the main cable sheath and prevent current from the bridge reaching the cable system. Where, after this was done, considerable potential differences were found to exist across the outer ends of the cable sheaths, these were equalized by connecting the cable sheaths at the two ends together by an insulated wire.

A simple and cheap form of insulating joint for lead cable sheaths which has been very generally used consists in cutting out a narrow strip of lead and covering the break with a suitable insulating and waterproof material so as to effectively prevent entrance of moisture.

This method of protecting underground structures has not been widely used as a primary means of electrolysis protection, partly because of the great expense involved. Further, insulating joints unless used with caution may introduce serious trouble at many points. This method has proved useful especially in certain new installations, but to protect existing installations by this means would involve prohibitive cost. It is usually regarded as a suitable auxiliary measure to be used in certain cases which cannot economically be taken care of by other means.

55. Insulating Pipes, Cables and Structural Steel from Earth. Many attempts have been made in practice to protect underground pipes from electrolysis by insulating the pipes from earth by paints, dips or insulating coverings. It has been found, however, that no dip or paint will permanently protect a pipe from electrolysis in wet soil. The first difficulty that is met is to apply the paint so as to form an absolutely perfect coating, and then to prevent mechanical damage to the coating. Where a coated pipe is in a positive area it has been found that aggravated trouble from rapid destruction of the pipe has resulted at spots in the pipe where there are imperfections in the coating. It has further been found that even where paints or dips are apparently intact, electrolytic action has taken place causing severe pitting under apparently good coatings. It has been found that in most cases the coatings applied have either been completely destroyed by the effects of the wet soil and electric currents, or defects in the coating have developed, causing concentrated corrosion at such defective spots. It has, in fact, been found that pipes located in positive areas covered with imperfect insulating coatings are more rapidly destroyed by electrolysis than bare pipes under the same conditions. It has been found that coating pipes in negative areas with insulating coverings accomplishes some good by reducing the amount of stray current which reaches the pipe.

Investigations indicate that the destruction of paints in wet soil where subjected to an electric current is probably due to a trace of moisture finding its way through the coating, giving rise to the flow of a feeble current and resulting in a very slight amount of electrolysis. The gases and other products of electrolysis then form blisters and finally rupture the coating.

Attempts have been made in practice to apply a molten material like pitch or asphaltum to a cold pipe in the field by means of brushes, but it has been found impossible to completely cover the pipe in this way. A type of insulating covering which has been successfully applied in a number of installations, and which appears to afford certain protection, consists of a layer of at least from 1 to 2 inches of a material like pitch or parolite of such a grade that it is not brittle and so will not crack, but yet is hard enough to remain in place. It has been found best to apply such a layer by surrounding the pipe with a wooden box, supporting the pipe upon creosoted blocks of wood or upon blocks of glass, and then filling the space between the box and the pipe with the molten material. The cost of carrying out such an installation is, however, large. The method has been applied in special cases, such as service pipes in very bad localities, and in the case of some very important individual pipe lines of comparatively small size.

Attempts have been made to protect a pipe from electrolysis by imbedding it in cement or concrete, but these attempts have not been successful, even where the cement or concrete was several inches in thickness. The reason for this is that concrete in damp earth acts as an electrolytic conductor, like damp soil, and therefore cannot afford protection from electrolysis.

The following experience and practice is that of a gas company in a large city which uses cast-iron pipes in general in their distributing system with wrought-iron services. They make it a uniform practice to protect all of their service pipes with an insulating coating. As a preliminary the pipes are first cleaned with a wire brush, in order to remove all scale. They are then dipped into a hot coal tar compound, then wrapped for the entire length with a strip of canvas, and then again dipped in the compound. In spite of this protection, however, they have some trouble with their services. The difficulty is due to their inability to get a continuous coating over the entire surface of the pipe. Small pin holes are left in the coating due to minute bubbles of air, or some similar cause, so that if the pipes are positive the flow of current from the pipe through moist earth is confined to these minute pin holes through the insulating compound. The result is that the action of the current forms a small blister of iron rust at the point where the pin hole is located, and after the blister becomes so large as to loosen a piece of the compound, the action takes place at a very rapid rate and soon destroys the pipe. In some locations some of the service pipes have to be renewed within a period of six months on account of the leaks caused by the electrolytic corrosion.

Attempts have been made to insulate lead-sheathed cables from earth, but these attempts have not generally been attended with beneficial results. The experience of the telephone companies, who are the largest users of lead-sheathed cables, has been that it is futile to attempt to insulate lead-sheathed cables from earth. It is, however, the practice of the telephone companies to make every effort to prevent metallic contact between their lead-sheathed cables and other grounded structures throughout the run of the cable, except where it has been determined by a careful survey that a drainage connection to some particular structure is required for the protection of the cable.

The use of insulating ducts has been proposed at various times, but investigations of the telephone companies do not show that their use affords satisfactory insulation of the cable sheaths from earth, with the result that the telephone companies do not place any reliance in any insulating property that any of the duct material may inherently possess. The principal duct material at present used by the telephone companies for main cable subway runs is vitrified clay and creosoted wood. For laterals and short cable runs iron pipe is frequently used.

Laying telephone cables in troughs and surrounding them solidly with asphalt was a method employed in the early days of telephone construction, but this method was abandoned because of its inflexibility and because of the great difficulty of repairing defects or replacing cables. It was further found that this method did not positively insulate the cables everywhere from earth on account of cracks and other discontinuities in the asphalt which were found in practice to develop.

Steel tape armored cables protected with a thoroughly saturated jute covering have been used buried directly in earth. Such covering has been found to be effective for a number of years in protecting the armor against electrolytic corrosion, except at points where the jute has been abraded or cut so as to expose the metal.

Where steel structures extending underground are located so as to be subjected to electrolytic action, the portions below ground have been enclosed with insulating materials. For this purpose any material that excludes water, as for instance paints having an asphalt base, have been successfully used, while many of the ordinary paints have not been found effective. It has also been found that surrounding steel with concrete where this is imbedded in damp earth does not afford absolute protection against electrolysis, although the electrolytic action is most severe at first and becomes less with time, because the formation of chalk in the concrete fills the pores of the concrete and increases its resistance and the iron oxide forming on the surface of the metal also increases the resistance. Special preparations of Portland cement properly applied so as to be watertight have also been found to afford good protection.

56. Shielding, or the Use of an Auxiliary Anode. In some special cases underground structures have been protected from electrolysis by connecting to the structure an auxiliary metallic conductor located so as to cause the current to flow to earth from the auxiliary conductor. This mode of protection is known as shielding. When applying this method it has been found necessary to take care that the auxiliary shielding conductor does not merely increase the electrode areas from which the current leaves, because in this case the current will continue to leave from the structure which is to be protected. This has been found to be the practical result where a shielding conductor of the same or less contact area was placed in earth near the structure to be protected and where the stray current then left from both structures. The shielding conductor must be so placed that current will be prevented from leaving the structure to be protected or so as to cause its magnitude to be greatly reduced. The method has in some installations been applied to a structure which forms the dead end of an underground metallic system and where the structure is highly positive to earth. In cases of this kind it has been found that the current leaves at relatively high density from and near the dead end of the structure, with the result of rapid destruction of the portion near its dead end. In such cases an auxiliary shielding conductor of adequate contact surface extending beyond the dead end and electrically connected to the structure to be protected has been installed in such a manner that the bulk of the current was caused to leave the auxiliary shielding conductor, thus affording a certain degree of protection to the dead end of the structure.

The shielding method has also been effectively applied for the protection of relatively small iron or steel pipes, such as service pipes. In these cases the service pipe has been surrounded by a larger metal pipe electrically connected to the smaller pipe. One application of this method which is in use is that of a service pipe crossing under tracks or crossing other structures to which it is positive and where the pipe comes relatively close to the rails or other structures at the point of crossing. In these cases a larger shielding pipe, usually of heavy cast iron, has been placed around the service pipe and electrically connected to the service pipe and extended sufficiently on each side of the crossing so that the major part of the current was caused to leave the shielding pipe, thereby corroding the shielding pipe while protecting the service pipe.

57. Drainage of Earthed Metallic Structures.

(a) Lead-sheathed Telephone and Power Cables. The method of protection against electrolysis used generally by telephone companies for their cable sheaths consists of installing insulated conductors, called drainage wires, between the negative return system of the railway and points on the cable system where the positive potential to earth is highest. The purpose of these drainage wires is to conduct the stray railway current from the cable sheaths to the railway negative return circuit, thereby preventing this current from flowing from the cable sheaths to earth and causing corrosion from electrolysis. In order to afford complete protection it has been found that such drainage wires must have sufficient conductivity and must be so located that the lead sheath of the cable network is everywhere lower in potential than the adjacent earth.

As the potential of the cable sheath is lowered by the connection of the drainage wire from the railway negative return circuit the current flowing on the cable sheath is thereby increased. In order that this current does not become excessive, care is taken to prevent contacts between cable sheaths and other underground structures, through which currents could flow to the cable sheaths.

The drainage method is also employed to a considerable extent for the protection of underground power cables, and the principles involved in its application are the same as for telephone cables. When power cables are worked at relatively high temperatures they should not also carry a heavy drainage current which might cause over heating. Where such conditions prevail drainage is not employed, but insulating joints are used to break up the continuity of the lead sheaths.

(b) **Pipe Systems:** The early success of the drainage method in affording protection against electrolysis of lead-sheathed cables led to the proposal to apply the same method of protection to underground piping systems. The result has been that in some cases drainage has been applied to gas and water piping systems to a greater or lesser extent. Some of these installations are reported to be a success, while others are reported to have been attended with objectionable results.

It has been found that there are certain differences between the application of drainage to pipes and the application of drainage to cable sheaths. The principal difference that has been found is that the cable sheaths are electrically continuous and uniform conductors, while the pipes are generally non-uniform and sometimes discontinuous conductors, by reason of the joints. It is found that where current flows along a pipe and encounters a high resistance joint, part of the current will leave the pipe on the positive side of the joint to flow to some other underground conductor or to shunt around the joint and thereby cause electrolytic corrosion of the pipe on the positive side of the joint.

Another difference between lead-sheathed cables and piping systems is that the cables are relatively small and are contained in ducts, so that unless they are submerged they are not in direct contact with earth, except at infrequent points, whereas gas and water pipes form extensive systems and are buried directly in earth. It is found as a result of this that a drainage connection from an underground piping system generally causes very much larger currents to flow on the piping system than a drainage connection from an underground cable system.

In the application of the drainage system it has been found that unless all sub-surface metallic structures affected by stray currents have been bonded together in such a way that at every point where the different structures come into proximity to one another all are maintained at the same potential, damage to the unconnected structures has in certain instances resulted from a flow of current through earth from the structure of higher to that of lower potential, thus causing electrolysis of the former. As structures owned by different interests cannot be bonded together except by an agreement between the owners, this has frequently of itself made it impossible to apply a comprehensive drainage system to all structures, because of the impossibility of obtaining an agreement of all owners to allow connections to their structures, except on condition that another interest assume liability for any injury which may result from such connections.

Current flowing on piping systems which convey inflammable substances such as gas or oil constitutes a danger, as cases have been reported where stray currents on pipes have caused arcs which have ignited the gas or oil when an intentional or accidental break in the pipe has occurred. In other instances serious damage from explosions and fire has been caused by an arc due to the intermittent contact between pipes.

(c.) **Structural Steel.** In a number of installations special precautions have been taken to prevent stray current from reaching structural steel. Where in these cases such currents were found to reach the structure by means of pipes or other metallic connections, insulating joints have been placed in such connections, or these pipes or conductors have been carried on insulated supports. In some cases where flow of stray currents to a steel structure could not be entirely prevented, drainage connections from the structure to the railway negative return circuit have been installed to remove the stray current from the structure, and where there were expansion joints in the structure these have been bonded across by metallic conductors.

C. PATENTED PROTECTIVE SYSTEMS.

58. Foreign and Domestic Patents. There have been many patents taken out in this country and abroad within the last twenty years, covering systems of electrolysis mitigation. Reference may be had to Technologic Paper No. 52 issued by the Bureau of Standards, Washington, D. C.

D. ORDINANCES AND DECISIONS.

59. Ordinances. A number of cities have ordinances directed to the construction and operation of electric railways. The Committee, however, does not possess sufficiently definite information as to the extent to which they have been put into effect or the results secured to warrant it in stating any facts regarding them at present.

60. Decisions of Courts. While there have been several cases of electrolysis litigation in this country each of these has either been concerned only with certain phases of the subject or has been limited by local conditions, so that there are no leading decisions by courts in this country which define specifically the duties and rights of the several parties concerned.

IV. EUROPEAN PRACTICE.

A. GENERAL.

61. Personal Investigation Necessary. In the study of the practice followed in European countries in handling the problem of electrolysis, it appeared impossible to secure reliable and satisfactory information by mere correspondence and consultation of published reports and regulations; and further, since the important independent investigations made by American investigators several years ago were private and made from the standpoint of some special industry rather than from a comprehensive all-around point of view the necessity of an independent investigation was made evident.

The Chairman of this Sub-Committee, after consultation with its members and the General Chairman decided to visit several important European countries during the summer of 1914. He was accompanied by Mr. A. Maxwell, Testing Officer of The New York Edison Company, who was thoroughly conversant with electrolysis measurements and surveys. The effort to have the Bureau of Standards appoint a representative to join the visiting representatives failed on account of extensive engagements of the Bureau, but a consultation was held in Washington, and the field of inquiry and special points to be looked after were carefully discussed, and a list of classified questions prepared, so that as far as possible uniformity of system of investigation could be followed in all instances. Similar consultations were held with members of the main Committee. Information on important foreign cities and authorities, was received from Mr. H. S. Warren, also foreign papers, suggestions and references from Prof. Albert F. Ganz.

62. Countries Visited. The visiting Committee spent June and July in its investigation, covering Germany, Italy, France and England. In each country an effort was made to take measurements and collect data and surveys, also to interview the most prominent people in each branch of the different interests affected by the problem of electrolysis; in each case extended and often repeated conferences were held with the engineers most familiar with the details, either in their capacity of specialized consulting engineers or officials of corporations or public authorities directly concerned in the surveys, disputes, administrative measures, etc. relating to electrolysis.

The essential and characteristic results of the investigation are briefly outlined in the following paragraphs, classified by countries visited. The references and appendixes to this summary should be consulted for details of design, operation and statistical information.

B. GERMANY.

63. Laws and Ordinances. There are no specific statutory laws. The common law of most States prescribes that all the conditions under which a corporation is to operate must be prescribed in the original grant or for any extension of lines, and the law prescribes that due publicity be given to any request for a franchise or extension of lines, so as to enable all parties which may be affected to place on record any limitation, or possible damage they wish to be protected against, before the concession is granted to the applicant. Hence, a pipe owning company organized subsequently to the existence of an electric railway, could not claim damages for electrolysis from this electric railway unless the original franchise to the railway contained a clause regarding electrolysis damages from stray currents.

On the other hand, when the municipality undertakes the construction and operation of a tramway system, the pipe owning companies then in existence are deprived of the privilege of demanding that protection against possible future damages by electrolysis which would be accorded to them in the case of a new private railway company. The municipality does not assume legally the obligation to protect the existing interests against possible damages by electrolysis. The municipalities, however, both for their new railway constructions, as well as for new extensions of existing companies' railways, always prescribe that they be constructed and operated in accordance with existing technical standards.

The recommendations of the German Earth Current Commission are recognized as the existing technical standards regarding matters relating to electrolysis, and in this manner they have assumed almost the importance of law.

64. Commission Recommendations. The German Earth Current Commission's recommendations adopted in 1910 by the German Electrotechnical Society prescribe the following:

In large cities, the maximum rail drop is to be limited, in the urban net-work and for a distance of 2 km. beyond, to 2.5 volts and to 1 volt per km. beyond this central district. Exceptions are made for roads operating only a few hours a day. (It may be noted here that the maximum drop is interpreted to be the average maximum drop for the period of the normal day traffic, usually 18 hours in every 24 hours.) Bonds must not increase the resistance of tracks over 20%—must be tested yearly and when a connection shows a resistance higher than 10 meters of rail it must be repaired. Connections to pipes are prohibited. Bare feeder returns are not allowed. Pilot wires are prescribed.

Since these regulations were promulgated from 20 to 30 installations in Germany (some municipally owned and some privately) have taken steps to bring up their standard of construction to meet these regulations.

65. Construction. In large cities, like Berlin, the railways are supplied by a great number of combination light and railway substations feeding limited districts, entailing relatively small positive line drops of potential. In some cases like Berlin, each feeding point is fed by positive and negative cables of equal cross-section.

Insulated returns with balancing resistances are predominantly used in Germany, though there are a few installations with negative boosters, like Danzig, where, however, insulated returns with balancing resistances as well as boosters are used.

There are very few large installations using bare returns. The "drainage system" was used in Aachen but it is now a subject of litigation.

66. Conditions. In general the electrolysis conditions throughout Germany are now very satisfactory. In the past the majority of troubles have been on gas and water pipes, or at least these have received more attention in the reports. The railway experts expressed the opinion that the regulations were too stringent; the gas and water pipe experts expressed the opinion that the regulations were too lenient. The studies are made in the most excellent technical manner and the conclusions arrived at appear to be practicable and reasonably acceptable to all parties concerned.

Measurements were made by the Sub-Committee of one large installation and it was found that the maximum drops in rails were well within the limits prescribed by the German regulations. More extended measurements were omitted, depending for other information on the surveys made by the German Earth Current Commission.

C. ITALY.

67. Laws and Ordinances. The Government has not enacted any law affecting the operation of electric railways in relation to electrolysis problems, nor has any municipality issued regulations on the subject.

68. Construction. Bare returns are generally used, in large installations.

69. Conditions. From a survey made in a city six years ago, it was found that the maximum differences of rail potential were as great as 17.5 volts between station and distant points about three miles away. In this installation they had not received complaints of serious damages by electrolysis, except a few gas service pipes, though the railroad itself had experienced some difficulties on water pipes at one of its yards.

Some of the larger systems in important cities are alive to the situation and are following with interest the developments in other countries.

In general, troubles from electrolysis have been considered insignificant in the Italian practice.

D. FRANCE.

70. Laws and Ordinances. A Ministerial Decree of March 21, 1911, prescribes that the maximum voltage drop in rail returns of *electric tramways* shall not exceed *one volt per kilometer*, except in locations where there do not exist metallic masses in the neighborhood of the tracks, where the limit may be exceeded. No definition is given of the time element in the measurement of the maximum drop, except by stating that it must be the average during the normal passage of the cars. The same decree prescribes that the bonds must be kept in the best possible condition, that the resistance of each must not be greater than 10 metres of normal rail and that periodic tests must be made and recorded on a register which must be subject to inspection on the call of the control service. The return feeders must be insulated.

71. Construction. While the Government regulations prescribe the use of insulated returns, we were informed that in general the practice is to connect the rails to the negative bus and to rarely use insulated returns. Noticeable exceptions are the Paris conduit system tramways using complete insulated returns, and the Paris Nord-Sud Subway Company operating a three wire system with the rails as neutral.

72. Conditions. The investigation was somewhat limited in France. In general serious electrolysis troubles were found only in a few situations, either created by installations of heavy traffic electric lines, or by peculiar conditions not readily explainable. The maximum drop of potential between pipe and rail measured by this Committee was about 6 volts at a location where trouble has been persistent and serious.

Damage has been caused in the past to gas pipes in Paris during the period of transformation of the old two-wire, three-wire and five-wire systems of electric light distribution, but all of these troubles were only of temporary character and were promptly remedied as soon as discovered.

Many suits (about twenty) for electrolysis damages are being tried in Paris. On account of the situation created by these suits the Paris municipality and the government have recently appointed a Commission to investigate the subject and make recommendations regarding the electrolysis situation in the City of Paris.

E. ENGLAND.

73. Laws and Ordinances. The Board of Trade regulations prescribe that the maximum rail drop shall not exceed seven volts. In practice the Board takes as the voltage drop the mean between the average and the momentary maximum values for the period of a schedule run at time of maximum traffic, exclusive of exceptional occasions like athletic games, etc. The periods assumed vary from 15 to 30 minutes. The regulations also contain other requirements, prescribing measurements of track leakage, etc.; in actual practice, however, little attention is paid to any other requirements as long as the seven volt over-all rail drop is not exceeded.

74. Construction. Whenever the resistance of the rails would give a drop in excess of seven volts, insulated return feeders with resistances, or negative boosters are used; the latter more extensively than in any other country.

75. Conditions. The sub-committee found that in all the several cities visited the Board of Trade regulations were met well within the limits. In fact, on the average the maximum drops measured in all large cities visited in the months of June and July were about two volts.

The Board of Trade regulations are not considered onerous by any of the railway engineers we consulted. All authorities representing the pipe owning companies, the railways, the State telegraph and telephone and the Board of Trade were unanimous in stating that the electrolysis situation on the properties under their respective control was entirely satisfactory.

The only question raised, and this only by a limited number of pipe owning entities, is whether the electric railways should not be held legally responsible for any damages, even when they comply with the Board of Trade regulations. Two or three attempts have been made to have a law passed by the Parliament to this effect, and two or three pipe exhibits have been repeatedly presented to prove electrolysis damages, but the Parliament refused to act.

The seven volt limitation is considered somewhat of a haphazard empirical measure formulated many years ago, but having given good results it is considered good enough, though it is conceded that some more rational measure could probably now be devised to replace it. However, no demand was discovered for a change on the part of anyone concerned.

F. SUMMARY AND CONCLUSIONS.

76. Germany through voluntary co-operation has probably remedied the former dangerous electrolysis conditions in all of its important systems. The instrumentality of agreements on definite technical standards was sought in preference to legislation for different states.

Italy will probably give more consideration to the subject of electrolysis whenever the general conditions will permit.

France has not been as successful in bringing prompt results through legislation, as has Germany through technical co-operation.

England, which has had the benefit of Government regulation for many years, has now no electrolysis troubles nor disputes.

In Germany and England, the subject of electrolysis has received extensive study and consideration. The attached typical abstracts of reports of the German Earth Current Commission and the appendix of the detail report of the Sub-Committee are evidence of the methods followed and the satisfactory results obtained abroad by adopting the following measures:

1st. Maintenance of good bonding.

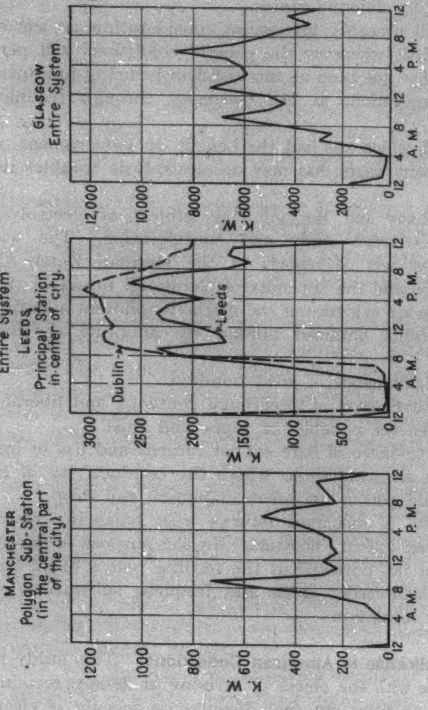
2nd. Elimination of intentional contacts, and liberal separation, whenever possible, of pipes and rails.

3rd. Avoidance of bare copper returns and use of insulated returns in all installations where the conductivity of the rail alone would give a too great maximum rail drop.

4th. Use of insulated returns with balancing resistances, or to a lesser extent "boosters," for the purpose of maintaining equality of rail potential at the feeding points of all feeders.

5th. Small feeder drops and frequent substations to give close line regulation.

77. Application to American Conditions. This study has not been made with the object of arriving at definite recommendations, but to point out that disputes on account of electrolysis troubles have been prevalent in the past in all countries before systematic cooperative studies or regulations had been applied, notwithstanding the fact that the mode of life and distribution of population and industries are more favorable than in American cities. The average weight of cars in foreign cities is essen-



Typical Load Curves, Electric Railways, – United Kingdom

Figure 6

tially less than in most American cities of the same population and the tramway traffic and loads per capita may be one-fifth or even less in Europe than in America. A city like Berlin with over 2,000,000 inhabitants handles all its transportation with a maximum load of about 30,000 k.w. (Chicago and the adjacent territory with 2,600,000 population requires a maximum load of about 200,000 k. w.) Manchester with a population of 1,250,000 and Glasgow with 1,000,000 have traction loads of 11,000 k. w. and 11,500 k. w. respectively. (Boston and the surrounding territory served by the same traction system has an approximate population of 1,150,000 and requires a power station capacity of 75,000 k. w.) Milan with a population of over 600,000 inhabitants has a traction load of approximately 8,000 k. w. and Nürnberg with 350,000 inhabitants uses only 1000 k. w. (The city of Worcester, Mass. with a population of approximately 160,000 requires power station capacity of 7,500 k. w.) These comparisons should not be taken as a definite index to comparative electrolysis conditions since many other factors are involved.

Other similar statistics for smaller places are given in Figure 6, and they should be taken in consideration in applying to this country the results of this investigation of foreign practice. Regardless of the degree of improvement which economical limitations may make permissible to accomplish in local situations, the fundamentals for the solution of the electrolysis problem evolved abroad merit the most careful study to ascertain their possible application to American conditions.

G. REGULATIONS ADOPTED AND PROPOSED.

78. Germany—Earth Current Commission's Recommendations. Recommendations of the German Earth Current Commission as adopted by the Gas, Water and Railway Interests of Germany.

> Regulations for the protection of gas and water mains from the electrolytic action of currents from direct current Electric Railways which use the rails as a return.
>
> Accepted for two years at the yearly meeting of 1910 and for a further two years at the yearly meeting of 1912.
>
> Published in the *Electrotechnische Zeitschrift* 1910, page 491, and 1911, page 511.

SECTION 1. APPLICATION OF RULES.

The following rules govern the installation of direct current railways or sections of direct current railways which use the rails for carrying the return current. Unless otherwise mentioned the herein given admissible potential values should be adhered to when laying out new railways. For determining the resistance of a line, the rails only must be taken into account as current carrying mediums and the assumed resistance of the rails, as well as the assumed percentage increase of resistance due to the bonding, must be stated.

These values must not be exceeded, either when making the necessary calculations or by the plant when in actual normal operation.

These rules do not apply when railways are laid with special track or when the rails are laid on wooden sleepers, in which case there is generally an air clearance between the rails and the stone ballast. But the rules do apply if this air clearance does not exist, as at grade crossings, unless an equivalent insulation is provided for locally. Further, these rules do not apply to railway lines which do not approach closer than 200 meters to an underground pipe network.

EXPLANATION.*

The regulations apply only to direct current railroads or sections of such, using the rails as conductors. Railroads not using the rails as conductors are eliminated from the start, because the same do not send any currents into the earth and therefore cannot have any damaging influence on the pipes. According to the experience reached so far, alternating current seems to have very little effect, so that any extension of these rules to cover also alternating current railways does not seem justified. At any rate, the conditions produced by alternating current railways are not yet sufficiently understood to allow of establishing any restrictions in regard to their equipment and operation for the protection of pipes.

In case a railroad is operated partly with direct current and partly with alternating current, these regulations apply only to those sections the rails of which carry direct current. The fixed upper limits of permissible potentials apply to the design of the plant, unless otherwise stated, and in the

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***NOTE**: This explanation and the others following are included in the German Earth Current Committees Recommendations.**

calculations only the rails and the bonds are to be considered as far as the conductivity and the resistances of the conductors are concerned. The assumed resistance of the rails and the increase of same by the resistance of the bonds is to be stated, and such limiting values are not to be exceeded either by calculations or in practice.

The earth as a shunt is not considered. Through contact of the rail network with the ground, a part of the current passes into the ground and the potentials of the rail network are thereby lowered as compared with a case of perfect insulation from the ground, the effect becoming greater, the more the current passes into the ground. It is, therefore, not correct to take the differences of potentials as found immediately after the construction of a rail network as a basis for estimating the safety against damaging influences, but it is necessary to go back to the first cause, that is to say, the differences of potential as they would be if the rails were completely insulated.

This rule allows of an exact calculation of the conditions during the design of the plant without any uncertain and varying values for different localities. The limit values are not to be exceeded either during the calculations or at the actual practical test. The method of the practical test will be discussed in Section 3. The projection of the plant is, therefore, to be based on assumptions as correct as possible with regard to the resistance of the rail, the cables, and the consumption of current, and it is advisable to consider also a later increase of the traffic.

Railroads, the rails of which are insulated on special roadbeds, generally have such a great resistance against the earth that passage of current into the ground to be considered as dangerous to pipes does not occur. Higher potentials, therefore, are permissible for such railroads, assuming that a sufficient insulation is provided for also on grade crossings, etc.

As a means to this end are to be considered:

Insulating strata between rails and ground, for instance, tar paper, which must extend on all sides sufficiently beyond the place in question; or the surrounding of the pipes with insulating material. Such places are to be inspected from time to time to ascertain the effect of such insulation.

For the exemption from these regulations the laying of the rails on a special roadbed is required, because it is only in this way that a permanent insulation can be reached and maintained. About the details of the system of insulation to be used, no rules were issued. A lasting insulation is to be guaranteed by the way in which the rails are laid. The laying of rails on wooden ties as mentioned above is intended as an example only. At any rate to secure satisfactory insulation it is imperative that the rails be nowhere in contact with the moisture of the ground, as this greatly favors the passage of the current into the ground.

Tracks which are at all points at least 200 m. distant from any pipes are exempt, because any current coming over such an extended area spreads to such a degree that its density cannot possibly be harmful. In this respect concession has been made to long outlying railway lines because the subjection of such to these regulations would entail great economic disadvantages in certain cases. The maintenance of good conductivity on such outlying sections is to be strongly recommended so as to prevent the return currents from reaching a dangerous density where such sections join the rails of an inner rail network, *i.e.*, a density exceeding the limit given in Section 5.

SECTION 2. RAIL CONDUCTORS.

All rails serving as return conductors should be built with regard to this requirement, should be made as good conductors as possible and should always be kept in good order.

The percentage of increase of the resistance of a given length of track due to the bonding should not exceed the value assumed when laying out the railway, and must not be more than 20% more than the resistance of the same length of track if the rails were without joints and of the same cross section and the same specific conductivity. On laying out a railway line consisting of main and auxiliary rails, the combined cross section of both rails can only be taken into account when determining the resistance of the track, provided the auxiliary as well as the main rails are properly bonded and cross bonded.

At rail crossings and at switches, the rails must be well bonded by special bridge bonds.

On single tracks as well as on lines where several tracks are lying side by side the rails must be efficiently cross bonded and these cross and bridge bonds must have a conductivity at least equal to a copper conductor of 80 square millimeters.

At all movable bridges or similar structures which necessitate an interruption of the rails, special insulated conductors have to be provided which secure a continuous connection between the two rail ends. In such cases, the voltage drop at average load must not exceed 5 millivolts for each meter distance between the interrupted rails.

All current carrying conductors which are connected to the rails, must be insulated from earth, excepting short connections such as bonds, cross-bonds and bridge-bonds at switches and turntables. If such bonds are laid not deeper than 25 centimeters into the earth, they may be bare conductors.

EXPLANATION.

The first condition for the reduction of stray currents and for the effectiveness of all the proposed precautionary measures, is the good conductivity of the tracks and the maintenance of this conductivity. High resistances of the single sections cause an increase of the current passing into the ground. The maintenance of the good conductivity of the rails also is to the economic interest of the railroad, because a bad conductivity will, under certain circumstances, cause loss of energy.

It is not desirable to issue rules concerning the cross-sections of rails or for the conductivity of the steel because the cross-section and the chemical composition of the steel are both determined by mechanical considerations; the conductivity is dependent on the composition of the steel, while the conductance of the rail depends on both the conductivity and the profile.

The resistance of a rail network is widely influenced by the quality of the electrical connections of the rails at their joints.

The rules do not recommend one or another system of connections at the joints, but give data covering the permissible increase of the resistance by such connections.

In consideration of the varying resistance of rails of different profile, it is not possible to establish a uniform permissible resistance for a bond, but the permissible increase of the total resistance of a section by all the bonds is given. This increase must not be over 20%. Inside of these limits the designing engineer may assume any increase of the resistance by the bond, but it must be considered that the increase assumed must be permanently maintained later on (Compare Sections 6 and 3).

It will be well to assume during the design of the plant, the increase of resistance of the bonds as very near the permissible limit. This is very important when shorter rails are to be used, with the consequent greater number of joints, the maintenance of which is correspondingly more difficult and, therefore, an increase of resistance through deficient bonds to be expected. The conductivity of rails is to be ascertained on a number of samples before the rails are laid, so as to have a guarantee that the calculated resistance will correspond to the resistance of the finished network.

The measurement of the resistance is made by measuring the current and the potential on a rail as long as possible and insulated from its supports; the potential terminals should include a part of the circuit between the current contacts and they should be at least of 0.5 meter distant from these current contacts. A simple calculation gives the conductivity of the rail by using the value shown by ammeter and voltmeter. The conductivity of the rails now in use is generally found to be between 4 and 5.5 Siemens.

In cases where main and auxiliary rails are to be used and where the combined cross-section of both is taken into calculation, the conductivity of the auxiliary rail also is to be measured as the same may differ considerably from the conductivity of the main rail.

At crossings and switches a loosening of the rail connections will take place caused by the vibrations brought about by the passage of the rolling stock, for which reason such places are to be bridged specially by electrical conductors. The cross connections serve the purpose of eliminating differences of potentials between tracks running side by side and also to insure a good metallic connection between the rails on one side of a track in the case of a temporary low conductivity of single joints or interruptions.

It seems advisable in consideration of the different length of rails, not to give an absolute distance between the cross-connections, but to establish their number by the number of joints. The bonds and cross-connections may be of any material as long as their conductivity reaches at least that of a copper connector of 80 square mm. For the connection of interrupted tracks, as for instance at movable bridges, insulated cables are required because of the presence of water or other substances in the soil, which highly favor the passage of currents into the ground. The highest permissible drop in potential at average load has been fixed at 5 millivolts per meter distance between the places of interruption, to insure a small difference of potential between these points.

Furthermore care is to be taken that the tracks in a movable bridge are in good contact with the tracks on both sides of it. The following is an example of the calculation of a cable bridging across the gap.

When the distance between the tracks at the point of interruption equals 30 meters, the permissible difference of potential therefore is 5 × 30 which equals 150 millivolts. The current to be carried across is assumed to be 120 amperes and the length of cable 30 meters. Assuming a specific resistance of 17.5 milliohms per meter and square millimeter, the resulting cross-section is:

$$q = \frac{17.5 \times L\,I}{e} = \frac{17.5 \times 30 \times 120}{150} = 420 \text{ sq. mm.}$$

Inasmuch as the increase of the surface contact between the conductors and ground results in an increase of the current passing from the conductors into the ground, the conductors connected to the rails, especially those lying deep enough to come into contact with the moisture of the ground, are to be insulated conductors. Only short connections such as jumpers on crossings and switches, are exempt from this rule on account of the same not lying deeper than 25 cm. under the surface, which means that they hardly come into contact with the moisture of the ground. The increase of surface of the contacts with the ground by these conductors, is too small in proportion to the total surface of the rail network to cause any apprehension regarding the currents passing into the ground.

SECTION 3. RAIL POTENTIAL.

A railway network is divided into two sections, first, the open road connecting the various townships, and second, the urban network.

In the urban network and for a distance of 2 km. beyond, the voltage drop between any two rail points should never exceed 2.5 volts when the line is working under normal conditions, and the drop in the rails for each kilometer of open road should not exceed 1 volt. Occasional night cars are not to be considered in determining the average load.

In townships through which only a single line is run, without local rail network, the total voltage drop in the rails must not exceed 2.5 volts from end to end of the township's pipe network.

Any apparatus which is supplied with current and which is connected to the railway network must not increase the voltage drop above the stated limits.

If various railway systems are connected together either through the medium of the rails or through the power station, each system must fulfill the above conditions. A rail system in a township with an independent pipe network has to comply with the above regulations also.

Exceptions from these rules in regard to the voltage drop in a railway network are admissible if local conditions and service necessitate and justify such exceptions. If, for instance, the service—as is the case in freight yards—covers only a small portion of the day, the above limits of rail drops may be exceeded. In yards with a service up to 3 hours daily, double the above values are permitted, and with a service up to one hour, four times the above values are allowed.

Explanation.

As mentioned in Section 1, the rail network is to be considered as insulated from the ground, so that the earth as a shunt is not considered.

The resistances of the single sections are to be calculated from the resistance of the rails under observance of the rules in Sections 1 and 2.

For the calculation of the potentials the value of the average current is to be used, as the magnitude of electrolytic decomposition of the pipe metal depends on the quantity of current, that is to say, the product of current and time. The highest values have not to be considered for the calculations. To find the consumption of current the average service as per schedule has to serve as the base.

The average current consumed on single sections can be calculated from the number of car km. or ton km. to be covered, by using the value for the consumption of current which, according to experience, and in consideration of the local conditions, is used for one car km., or ton km.

But it is also permissible to distribute the consumption of current over the whole net in a way corresponding to the locations of the single trains at the time of the average load and to calculate for each train the consumption of current taking into consideration the weight of the cars, the speed and operating conditions (grades, stops).

In regard to the schedule, the difference between summer and winter service is to be considered. The increase at regular intervals, as for instance on Sundays, is to be taken into account. Small deviations from the schedule, as for instance, single night cars, or auxiliary cars, shall not be considered, because the first would reduce the average value out of proportion, and the frequency of the second cannot be estimated at the time of the calculations and otherwise are not of any appreciable influence on the final results.

It is impossible to get regulations embracing all conditions and possibilities and it is therefore necessary to consider all peculiarities of a plant during its projection. If there are any additional places connected to the rails, where current is used for stationary motors, station lighting, etc., these are to be considered.

After the drops in potential on the central sections have been tabulated, based on the above calculations, the distribution of the potential in the rail network can be found. In addition to the foregoing data for the calculation of the drop in potential on the single sections, consideration is to be given to the proposed return cables and, in case of a three wire system, to the direction of the current in the districts of different polarity.

Difference in potential between any two points of the rail network must answer the following conditions:

Around every individual pipe network (meaning a network not in metallic contact with any other network) and also around single pipes, a zone of two hundred m. is to be circumscribed and all tracks lying outside of this zone are not to be considered in connection with these regulations, as per last part of Section 1.

For each of the rail branches lying inside of these individual pipe networks, the following rules apply:

If there are any branches of the railroad inside of a pipe network, including the 200 m.-zones, a belt 2 km. wide is to be laid around the inner rail network. Inside this belt the potential of the rails between any different points must nowhere exceed 2.5 v., as long as no portion of the rails is more than 200 m. distant from the nearest pipe along its total length (Compare Fig. 7.).

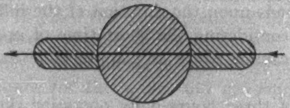
On the sections outside the 2.5 v. districts, the drop in potential must not exceed 1 v. per km. This applies to outlying sections which are shown in Fig. 7 by heavy dotted lines.

In the case of a railroad with no branches (country roads) and a pipe network, the drop in potential inside the pipe net work must not exceed 2.5 v. (Compare Fig. 8). The rule establishing a drop of 1 v. per km. states that the current in the track must not exceed $\frac{1}{W}$, if W is the resistance of the track in ohms per km. For a uniform load of a section of L km. length and a uniform resistance, the permissible drop in potential $= \frac{L}{2}$ v. *i.e.* $\frac{1}{2}$ drop in one rail. The calculation of this drop also is based on the average load, according to the schedule.

Strict rules have been issued for the interior rail network with its many branches, as it mostly covers the same area as the pipe network. This has been done in consideration of the greater surface of contact between ground and rails and pipes respectively which increases the probability of a passage of current through the ground. The potential of 2.5 volts for this district has been judged permissible because, according to the results of previous investigations, it is to be assumed that this potential will not under ordinary conditions cause any danger to pipe lines beyond the practical limits. To avoid as much as possible any greater concentrations of ground and pipe currents at the outlying sections which immediately join the inner rail network, and where important parts of the pipe network often extend, strict rules have been issued covering the district inside the 2 km. belt around the inner rail network.

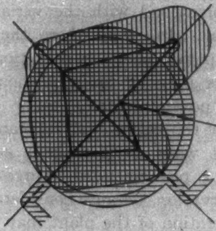
For the outlying section an economical advantage has been contemplated by limiting the drop in potential to 1 v. per km. Railroads interconnected by their rail networks or by a common power plant are to be considered as one system because such railroads influence each other, inasmuch as equalizing currents will flow between their rail networks.

Deviations in both directions from these potentials can be justified by certain circumstances—in case of especially good conditions of the ground, that is to say, in very dry dirt an increase of the potentials may be permissible. But even in such cases it is advisable to be cautious in allowing such an



▨ District of interior pipe-network.
▧ District of 200 m. around pipes with no branches.
— Railroads in the 2.5 V. District.
– – Railroads in the 1 V-Km District.
— Railroads with no Restrictions.

Figure 7



▤ District of the pipe-network with the 200 m. belt surrounding it and the pipes with no branches.
▥ District of the interior Rail-network with the 2 Km. belt surrounding it.
— Railroads in the 2.5 V. District (shaded by both horizontal and vertical lines).
– – Railroads in the 1 V.-Km. District (shaded by horizontal lines).
— Railroads with no restrictions (not shaded, or by vertical lines only).

Figure 8

increase, so as not to violate the rules as given in paragraph 5. Where the conditions are unfavorable, for instance, where moist ground of especially high conductivity prevails, it is advisable to remain below the limits. For railroads with brief daily operation concessions have been made because damage to the pipes depends upon the duration of the influence of the current so that, considering the short time of operation, even greater currents cannot cause any appreciable damage to the pipes.

For railroads of three hours daily operation double drop in potential is allowed, while for railroads of one hour operation, four times the drop is permissible. Wherever the rail network is not sufficient to carry the current without exceeding the permissible potential in the network, the whole plan for the return of the current must be altered, and improvement will be reached by providing return cables in which, if necessary, resistances or boosters may be inserted. The resistances should be variable so as to correspond with the variable conditions of service and operation. In cases where the railroad system is fed from several power plants a reduction of the drop in potential in the rails may be brought about by shifting the loads of the several power plants.

The arrangement of the cables and resistances can be made in so many different ways as to make a general rule for all cases impossible. It is recommended to investigate thoroughly the cases under observation, because considerable saving in the construction and operation of the plant may be achieved by a careful layout.

The keeping of the return points at the same potential is recommended as a precautionary measure but not required. The same offers a certain guarantee of the possibility to keep the difference of potential within the 2.5 V. limits.

Furthermore, the use of the 3 wire-system with the rails as a neutral conductor is worthy of consideration. In this system the difference of potential in the rails depends on the distribution of the positive and negative feeder districts. This distribution again depends on the local conditions of the plant, so that no general rules can be given in regard to it.

Alterations of the conditions of operation can be counteracted by switching the load to the positive or negative side of the system. The rules do not recommend any certain system, but leave it entirely to the projecting engineer to select the one best adapted to existing conditions. The damage to pipes takes place mostly at points of low potential on two-wire railroads, in the neighborhood of the return points; and on three-wire railroads, in the districts of negative feeders, because it is mainly here that the current leaves the pipes. It is advisable to place the return points of the negative feeder districts whenever possible in locations with dry ground of low conductivity and as far as possible from such pipe lines as are of importance for the water and gas supply.

The permissible limits of differences in potential in rails must not exceed, either according to calculations, or at the practical trial, the limits given in Section 1 of these rules. The measurement of the difference in potential is made by means of test wires as called for in Section 6. The measurements of differences in potential are limited to those points which, according to the calculations, come nearest to the established limits. Wherever long lines, as, for instance, telephone wires, are available, it is advisable to use them for these measurements, otherwise several test wires may be connected in series or temporary test lines may be installed: finally, the results of single measurements may be computed to reach the same final results. Only high resistance voltmeters should be used for these measurements so as to make the resistances of the test wire and contacts negligible. The pointers of these instruments should have the slowest movements and a good damper arrangement, so as to give good readings even under strong fluctuations. For all measurements only average values are considered. All measurements are to be extended over a full period of operation which results from the average frequency of trains.

SECTION 4. RESISTANCE BETWEEN RAIL AND EARTH.

The resistance between ground and the rail which is used for carrying the return current should be kept as high as possible. When the conditions of the ground or the situation of the track are not favorable for this purpose, the resistance should be increased by a special effective insulation.

The rails or any conductor connected to the rails must not be in contact with the pipes or any kind of metal buried in the ground. Furthermore, care must be taken that the distance between the nearest rail and any metallic part of the pipe lines or connections to them which project above the ground or lie near the surface, be kept as great as possible, and should never be less than one meter.

Stationary motors, lighting installations or any other plant which receives current from a railway system which uses the rails for carrying the return current, must be connected to the rail network by means of insulated conductors. Excepted are short connections of not more than 16 square millimeters which are not deeper than 25 centimeters in the ground and which are at a distance of at least 1 meter from any part of a pipe network. These connections may be of bare metal. In order to increase the resistance between rail and ground it is recommended to use a bedding of high resistance and to provide good drainage, also to render the bedding water-tight to the roadbed for a sufficient width on both sides of the rail.

The use of salt for the melting of snow and ice, should be limited to cases of absolute necessity.

Wherever sufficient distance between the rail and such parts of the pipe line as project above the surface is not obtainable, it is advisable to change the pipe run, or where this is not possible, to use insulating strata (such as vitrified clay, masonry or wooden conduits, etc.).

EXPLANATION.

The magnitude of currents passing into the ground depends not only on the potentials in the rail network, but also on the resistances between the rails and the pipes and on the resistances of the pipe lines themselves. It will always be of advantage to increase the resistance of the ground between the rails and the pipes. An artificial increase of the resistances of the pipe line can be achieved for instance, by the use of insulating flanges, couplings, etc. Aside from the technical difficulties of installing such insulating parts into gas pipes, and especially water pipes with a high pressure, and of insuring their lasting tightness, it would be difficult to provide these insulating pieces in the necessary numbers and to take care of their correct distribution. A wrong arrangement of the same will lead to an extraordinary concentration of currents at these insulations with consequent corrosion in these places. A greater part of the drop in potential between pipe and rail originally takes place in the roadbed as can be easily understood and it is therefore required to render this resistance as high as possible by the good insulation of the roadbed, good drainage, etc., and to maintain it thus.

In the same measure that the increase of the resistances between rail and pipe is recommended, the use of any means to reduce these resistances, is to be warned against. Such means to be considered are ground plates, connections of metals in the ground, and especially metallic connections between the rails and the pipes. The last will reduce the density of the current at the point of connection to the pipe, but they cause an increase of the pipe current and of the ground currents in general which may cause damage in other places, as, for instance, at interruptions in the pipe line or at crossings with other lines. Any local measure taken must be considered with regard to its effect on the pipes in other localities.

Metallic connections between different pipe networks also are to be judged from this viewpoint. Immediate contact of any parts of the pipe lines with the rails, or too close an approach, has the same effect as direct metallic connections and is, therefore, to be avoided. (By a re-location of rails or pipes or installation of insulating strata).

Especially in cases of stationary motors or lighting plants connected to the railroad system, there exists on the premises danger of an accidental or deliberate connection or contact with the pipe lines. It is, therefore, necessary to have strict rules regarding the return cables from such plants.

SECTION 5. CURRENT DENSITY.

The above rules are intended to prevent the destruction of the pipes by electrolysis. The rate of destruction is in direct proportion to the amount of current leaving the pipe.

Any pipe line where the current leaving the pipe exceeds an average density of 0.75 milliampere per square decimeter and where this current is due to a railway, may be considered endangered by this railway, and further preventive measures must be taken.

For railways with freight service when the service is of comparatively short duration, exceptions as already mentioned are permissible.

In cases where the current leaving or passing into the pipes changes its direction, the current passing into the pipe must be taken as nil when determining the average density, until further experience has been gained in this matter.

EXPLANATION.

Inasmuch as a total elimination of all damages to pipes would be in most cases possible only at a disproportionately high cost, which would far exceed the cost of any possible damage to the pipes, it is necessary to allow a certain limited damage, that is to say, a damage which is of little practical importance and which does not noticeably shorten the life of the pipes. These rules have therefore been compiled on the basis of the average conditions, that is to say, such as are mostly met with, and it is to be expected according to previous experience that the damage done to pipe lines by the stray currents from electrical railways, generally will remain limited to the practical allowable limit wherever these rules are observed. Under exceptionally bad conditions, that is to say, under conditions which very much favor the origin of stray currents, greater corrosion of pipes in certain places can hardly be avoided, even if the limits of the drop in the potential in the rails, as laid down in Section 3, are not exceeded. It is, therefore, advisable to establish some measure for the elimination of immediate danger to the pipes.

For the judgment of the damage attributed to a railroad system the density of the current leaving the pipes and returning to the railroad system is indicative.

The density of the current at the pipe can be measured only after the completion of the plant. These measurements must be made during the time of operation, as per schedule, and as described in Section 3. The average density is important and is obtained from the computation of the results of several measurements, each of which follows a whole period of service.

Measurements of current density can be made, for instance, by means of a milliammeter and non-polarizable frame as designed by Prof. Haber. This frame contains two copper plates which are insulated from each other and which for the prevention of polarization are covered with a paste of copper sulphate and 20% sulphuric acid, over which a parchment, soaked with sodium sulphate is laid. The frame is filled with dirt except between the plates, and placed alongside the pipe at right angles to the assumed direction of the current and then covered with dirt. A very sensitive ammeter connected to the copper plates will indicate the current passing through the frame and the density of this current can readily be calculated by taking into account the surface of the copper plates inside the frame. Inasmuch as here also only average readings are to be considered, it is advisable to use an instrument with very slow period.

According to investigations made so far, absolute danger to the pipes results whenever the density of the currents leaving the pipes reaches the average value of 0.75 milliampere per square dcm. For railroads with small periods of operation an excess up to double and quadruple, respectively, the above value is permissible according to the rules laid down in Section 3.

Wherever the direction of the current changes, the currents entering the pipes are not to be considered in the calculations of the average density, inasmuch as it is not as yet established that such currents will add to the metal of the pipes. Wherever the average values are exceeded, especial precautionary measures are to be taken, the nature of which can be determined only by the local conditions. In many cases it is sufficient to protect a very limited section of the rail network, to which end the further reduction of the drop in the rails may not be necessary, but which may be attained by other means as, for instance, the re-location of short sections of tracks or pipes, or the artificial increase of the resistances between rails and pipes at such points.

In all cases the question arises whether the railroad is to be considered as the only cause of current concentration, as other causes may be found to be responsible for a part of the current on the pipes; for instance, bare neutrals or poor insulation in other electrical systems, the natural electrical elements resulting from the use of different metals in the pipe lines, or from different chemicals in solution in the ground. That part of the current which is attributable to the influence of the railroad can be determined by comparison with the measurements of the current during the period of no operation. In many cases the influence of the railroad can be judged from contemporaneous measurements of current density and the potential between pipe and rail. Under certain circumstances it is possible to find the degree of influence of the railroad and of other electrical plants operating at the same time, by establishing the course of the current in the ground. For this investigation electrodes that cannot be polarized are used as contacts from the test line to the ground. The measurements should preferably be made by the potentiometer method in order to eliminate drop at the electrodes due to the current flow, but this method is difficult in practice on account of the rapid fluctuations of the voltage. It will be sufficient in most cases to make the measurements with a voltmeter of very high resistance so that the current passing through the electrodes will be very small. It should be emphasized that such measurements should be made by experts only, as deviations from the right method which seem of no importance often give useless results.

SECTION 6. CONTROL.

In order to be able to test the potential at the return points of the rail system of a given territory, pilot wires are to be connected to these points and carried to a central testing place.

Before a service may be increased the potential distribution in the rail network must be retested.

The rail bonds and bridge connections are to be retested once yearly by means of a suitable rail joint tester and must be arranged so that they fulfill the rules of Sections 1 and 2. Connections the resistance of which has been found greater than that of an uninterrupted rail of 10 meters length must be repaired to comply with these rules.

EXPLANATION.

The control of the drop in potential in the whole network would be best assured by the installation of test wires from one of the buses to all points of probable highest and lowest rail potential, which arrangement admits of immediate measurement of potential between these points.

In certain cases, especially in existing plants, the installation of such test wires would involve great cost. Such test wires from all of the important rail points were not required; but it has been ruled that all points of the rail network, to which cables of the same district are now connected, are to be provided with test wires which have to run to some central point where readings of the differences of potentials between the return points can be taken.

Wherever the expense involved permits, it is recommended to install test wires not only to the return points but also to the points of highest rail potentials.

After permanent changes in the operation, the distribution of the potential in the rail network is to be investigated in the same way as after the inauguration of the plant, in order to ascertain whether the new conditions still correspond to the rules.

In case of temporary changes of short duration in the whole network or parts of the same as, for instance, occasionally some festival, change or repair of tracks, fairs, exhibits, etc., no special measures are to be taken because the short duration of the influence will cause no noticeable damage even when the limits of these rules are exceeded.

The yearly investigation of the rail joints, as required by the rules, is also to be recommended with regard to the reduction of losses of energy. For these measurements an apparatus may be used which allows of the comparison of the drop in potentials across the joint with one of the adjoining uninterrupted rails so that the measurement may be taken during the operation. Joints of a resistance higher than that of an uninterrupted rail of 10 m. length are immediately to be repaired. The total resistance, as found by the measurement of the single joints, must not exceed the value which has been assumed during the projection of the plant (compare Section 2, paragraph 2).

Should it result during operation that rail joints are of a higher resistance than that assumed in the designing it is permissible to abstain from a re-construction of the joints as long as the permissible difference of potentials in the rails is not exceeded, even with these higher resistances. The established limits of 20% increase of the resistance of the uninterrupted rail by the bonds must not be exceeded in any case.

79. France—Regulations by Minister of Public Works Circular and order of the Minister of Public Works (France) of March 21, 1911, establishing the technical conditions which electrical distribution systems must satisfy in order to conform to the law of June 15, 1906. (Pages 25-27)

SECTION III. REGULATIONS RELATIVE TO THE CONSTRUCTION OF STRUCTURES FOR ELECTRIC RAILWAYS USING DIRECT CURRENT.[1]

DISTRIBUTION POTENTIAL FOR RAILWAYS.

ART. 27. The requirements of art. 3, paragraph 4; of art. 5 paragraph 26; 4 and 6 of art. 25, and of the first two sections of paragraph 3 of art. 31 do not refer to trolley wires, nor their supports, nor the other lines placed upon these supports, nor those not upon the public highway, nor those inaccessible to the public, if the potential between these conductors and ground is not greater than 1000 volts.

1. Electric traction projects using alternating current should be submitted to the Minister of Public Works in all cases where distribution is upon the public highway.

RIGHT OF WAY.

ART. 28. When the rails are used as conductors, all necessary measures should be taken to guard against the harmful action of stray currents, on metallic structures, such as the tracks of railways, the water and gas pipes, the telegraph or telephone lines and all other electric conductors, etc.

To this end the following regulations shall be applied:

1. The conductance of the tracks shall be known to be in the best possible condition, especially in regard to the joints, whose resistance should not exceed, in each case, that of 10 meters of the normal track.

The management is required to verify periodically this conductance and to place the results obtained on file, which shall be accessible to the administration upon demand.

2. The drop in potential in the rails, measured upon a length of track of 1 kilometer taken arbitrarily upon any section of the system, should not exceed an average value of 1 volt for the operating period of the normal car schedule.

3. The feeders tied into the track shall be insulated.

4. Where the tracks contain switches or crossings, the conductance shall be maintained by special work.

5. When the track crosses a metallic structure, it should be electrically insulated, as much as possible, throughout the length of the structure.

6. As long as no metallic structure is in the neighborhood of the tracks, a drop in potential greater than that fixed in paragraph 2 may be allowed, upon the condition that no damage will result, and particularly no trouble to telegraphic or telephonic communication, and none to railway signals.

7. The owner of the distribution system shall be required to make the installations necessary to enable the administration to verify the fulfillment of the provisions of this article; it should particularly provide, whenever necessary, for pilot

wires to be installed between designated points of the distribution system.

PROTECTION OF NEIGHBORING AERIAL LINES.

ART. 29. At all points where the lines feeding the traction system cross other distribution lines, or telegraph or telephone lines, the supports should be established with a view to protect mechanically these lines against contact with the aerial conductors feeding the traction system.

In all cases, measures shall be taken to prevent the trolley wire touching the neighboring lines.

80. England.—British Board of Trade Regulations. Regulations made by the Board of Trade under the provisions of Special Tramways Acts or Light Railway Orders authorizing "lines" on public roads; for regulating the use of electrical power; for preventing fusion or injurious electrolytic action of or on gas or water pipes or other metallic pipes, structures or substances; and for minimising as far as is reasonably practicable injurious interference with the electric wires, lines, and apparatus of parties other than the Company, and the currents therein, whether such lines do or do not use the earth as a return.

First made, March, 1894.
Revised, April, 1903.
Further revised, August, 1904.
Further revised, May, 1908.
Further revised, April, 1910.
Further revised, September, 1912.

REGULATIONS.

1. Any dynamo used as a generator shall be of such pattern and construction as to be capable of producing a continuous current without appreciable pulsation.

2. One of the two conductors used for transmitting energy from the generator to the motors shall be in every case insulated from earth, and is hereinafter referred to as the "line"; the other may be insulated throughout, or may be uninsulated in such parts and to such extent as is provided in the following regulations, and is hereinafter referred to as the "return."

> The Board of Trade will be prepared to consider the issue of regulations for the use of alternating currents for electrical traction on application.

3. Where any rails on which cars run or any conductors laid between or within three feet of such rails form any part of a return, such part may be uninsulated. All other returns or parts of a return shall be insulated, unless of such sectional area as will reduce the difference of potential between the ends of the uninsulated portion of the return below the limit laid down in Regulation 7.

4. When any uninsulated conductor laid between or within three feet of the rails forms any part of a return, it shall be electrically connected to the rails at distances apart not exceeding 100 feet by means of copper strips having a sectional area of at least one-sixteenth of a square inch, or by other means of equal conductivity.

5. (a) When any part of a return is uninsulated it shall be connected with the negative terminal of the generator, and in such case the negative terminal of the generator shall also be directly connected, through the current-indicator hereinafter mentioned, to two separate earth connections which shall be placed not less than 20 yards apart.

(b) The earth connections referred to in this regulation shall be constructed, laid and maintained, so as to secure electrical contact with the general mass of earth, and so that, if possible, an electromotive force, not exceeding four volts, shall suffice to produce a current of at least two amperes from one earth connection to the other through the earth, and a test shall be made once in every month to ascertain whether this requirement is complied with.

(c) Provided that in place of such two earth connections the Company may make one connection to a main for water supply of not less than three inches internal diameter, with the consent of the owner thereof and of the person supplying the water, and provided that where, from the nature of the soil or for other reasons, the Company can show to the satisfaction of the Board of Trade that the earth connections herein specified cannot be constructed and maintained without undue expense the provisions of this regulation shall not apply.

(d) No portion of either earth connection shall be placed within six feet of any pipe except a main for water supply of not less than three inches internal diameter which is metallically connected to the earth connections with the consents hereinbefore specified.

(e) When the generator is at a considerable distance from the tramway the uninsulated return shall be connected to the negative terminal of the generator by means of one or more insulated return conductors, and the generator shall have no other connection with earth; and in such case the end of each insulated return connected with the uninsulated return shall be connected also through a current indicator to two separate earth connections, or with the necessary consents to a main for water supply, or with the like consents to both in the manner prescribed in this regulation.

(f) The current indicator may consist of an indicator at the generating station connected by insulated wires to the terminals of a resistance interposed between the return and the earth connection or connections, or it may consist of a suitable low-resistance maximum demand indicator. The said resistance, or the resistance of the maximum demand indicator, shall be such that the maximum current laid down in Regulation 6 (I) shall produce a difference of potential not exceeding one volt between the terminals. The indicator shall be so constructed as to indicate correctly the current passing through the resistance when connected to the terminals by the insulated wires before-mentioned.

6. When the return is partly or entirely uninsulated the Company shall in the construction and maintenance of the tramway (a) so separate the uninsulated return from the general mass of earth, and from any pipe in the vicinity; (b) so connect together the several lengths of the rails; (c) adopt such means for reducing the difference produced by the current between the potential of the uninsulated return at any one point and the potential of the uninsulated return at any other point; and (d) so maintain the efficiency of the earth connections specified in the preceding regulations as to fulfill the following conditions, viz.:

> (I) That the current passing from the earth connections through the indicator to the generator or through the resistance to the insulated return shall not at any time exceed either two amperes per mile of single tramway line or five per cent of the total current output of the station.
>
> (II) That if at any time and at any place a test be made by connecting a galvanometer or other current-indicator to the uninsulated return and to any pipe in the vicinity, it shall always be possible to reverse the direction of any current indicated by interposing a battery of three Le-

> clanche cells connected in series if the direction of the current is from the return to the pipe, or by interposing one Leclanche cell if the direction of the current is from the pipe to the return.

The owner of any such pipe may require the Company to permit him at reasonable times and intervals to ascertain by test that the conditions specified in (II) are complied with as regards his pipe.

7. When the return is partly or entirely uninsulated a continuous record shall be kept by the Company of the difference of potential during the working of the tramway between points on the uninsulated return. If at any time such difference of potential between any two points exceeds the limit of *seven volts*, the Company shall take immediate steps to reduce it below that limit.

8. The current density in the rails shall not exceed nine amperes per square inch of the cross sectional area.

9. Every electrical connection with any pipe shall be so arranged as to admit of easy examination, and shall be tested by the Company at least once in every three months.

10. The insulation of the line and of the return when insulated, and of all feeders and other conductors, shall be so maintained that the leakage current shall not exceed one hundredth of an ampere per mile of tramway. The leakage current shall be ascertained not less frequently than once in every week before or after the hours of running when the line is fully charged. If at any time it should be found that the leakage current exceeds one-half of an ampere per mile of tramway the leak shall be localised and removed as soon as practicable, and the running of the cars shall be stopped unless the leak is localised and removed within 24 hours. Provided that where both line and return are placed within a conduit this regulation shall not apply.

11. The insulation resistance of all continuously insulated cables used for lines, for insulated returns, for feeders, or for other purposes, and laid below the surface of the ground, shall not be permitted to fall below the equivalent of 10 megohms for a length of one mile. A test of the insulation resistance of all such cables shall be made at least once in each month.

12. Any insulated return shall be placed parallel to and at a distance not exceeding three feet from the line when the line and return are both erected overhead, or eighteen inches when they are both laid underground.

13. In the disposition, connections, and working of feeders, the Company shall take all reasonable precautions to avoid injurious interference with any existing wires.

14. The Company shall so construct and maintain their system as to secure good contact between the motors and the line and return respectively.

15. The Company shall adopt the best means available to prevent the occurrence of undue sparking at the rubbing or rolling contacts in any place and in the construction and use of their generator and motors.

16. Where the line or return or both are laid in a conduit the following conditions shall be complied with in the construction and maintenance of such conduit:

> (a) The conduit shall be so constructed as to admit of examination of and access to the conductors contained therein and their insulators and supports.
>
> (b) It shall be so constructed as to be readily cleared of accumulation of dust or other debris, and no such accumulation shall be permitted to remain.
>
> (c) It shall be laid to such falls and so connected to sumps or other means of drainage, as to automatically clear itself of water without danger of the water reaching the level of the conductors.
>
> (d) If the conduit is formed of metal, all separate lengths shall be so jointed as to secure efficient metallic continuity for the passage of electric currents. Where the rails are used to form any part of the return they shall be electrically connected to the conduit by means of copper strips having a sectional area of at least one-sixteenth of a square inch, or other means of equal conductivity, at distances apart not exceeding 100 feet. Where the return is wholly insulated and contained within the conduit, the latter shall be connected to earth at the generating station or sub-station through a high resistance galvanometer suitable for the indication of any contact or partial contact of either the line or the return with the conduit.
>
> (e) If the conduit is formed of any non-metallic material not being of high insulating quality and impervious to moisture throughout, the conductors shall be carried on insulators the supports for which shall be in metallic contact with one another throughout.
>
> (f) The negative conductor shall be connected with earth at the station by a voltmeter and may also be connected with earth at the generating station or sub-station by an adjustable resistance and current-indicator. Neither conductor shall otherwise be permanently connected with earth.
>
> (g) The conductors shall be constructed in sections not exceeding one-half a mile in length, and in the event of a

leak occurring on either conductor that conductor shall at once be connected with the negative pole of the dynamo, and shall remain so connected until the leak can be removed.

(h) The leakage current shall be ascertained daily, before or after the hours of running, when the line is fully charged, and if at any time it shall be found to exceed one ampere per mile of tramway the leak shall be localised and removed as soon as practicable, and the running of the cars shall be stopped unless the leak is localised and removed within 24 hours.

17. The Company shall, so far as may be applicable to their system of working, keep records as specified below. These records shall, if and when required, be forwarded for the information of the Board of Trade.

Number of cars running.

Number of miles of single tramway line.

DAILY RECORDS.

Maximum working current.

Maximum working pressure.

Maximum current from the earth plates or water-pipe connections(vide Regulation 6 (I)) where the indicator is at the generating works.

Fall of potential in return (vide Regulation 7).

Leakage current (vide Regulation 16 (h)).

WEEKLY RECORDS.

Leakage current (vide Regulation 10).

Maximum current from the earth plates or water-pipe connections (vide Regulations 6 (I)) where a maximum demand indicator is used.

MONTHLY RECORDS.

Condition of earth connections (vide Regulation 5).

Minimum insulation resistance of insulated cables in megohms per mile (vide Regulation 11).

QUARTERLY RECORDS.

Conductance of connections to pipes (vide Regulation 9).

OCCASIONAL RECORDS.

Specimens of tests made under provisions of Regulation 6 (II.)

Board of Trade,
7, Whitehall Gardens, S. W.
September, 1912.

81. Spain—Electric Legislation. Law of March 23, 1900.

ARTICLE 50. To prevent the return current of electric tramway lines from exercising any electrolytic effects, the following measures shall be taken:

(1) The rails of each one of the tracks are bonded by welding or by connections formed of short copper cables, or of equivalent cables made of some other metal, the section of which having to exceed 100 square millimeters per track, and shall be made as large as possible.

(2) At intervals of 100 meters, or at shorter distances, the tracks shall be cross-bonded.

(3) In case the official inspector should deem it necessary, a cable will have to be stretched in every line, which will have to be intimately connected with both tracks; and

(4) The dimensions of all cables and wires constituting such system will have to be calculated upon a basis that the potential difference between the generator terminals and the point of the tracks remotest from them will not exceed an amount of seven volts.

H. SUMMARY OF EUROPEAN CONDITIONS.

Conditions in Germany, Italy, France and England as Reported to the Visiting Committee by Various Authorities in these Countries.

82. Present Electrolysis Conditions.

Germany. Considerable damage was found in many cities prior to the application of the Earth Current Commission's Regulations; in one case service pipe trouble occurred as often as once a month. Generally, however, extensive damage was not known until it was revealed by investigation; thus, many of the cities which were surveyed by the Commission, and where more or less corrosion was found, had previously reported no damage.

In general, the pipe owning interests stated that the situation was such that the work of the Earth Current Commission was urgently needed. Some railway engineers held that a considerable amount of corrosion ascribed to stray railway current was in fact due to other sources, or to self-corrosion.

Many very thorough tests have been made in Germany, and a large majority of these have shown that corrosion was being produced by stray railway currents.

The more prosperous companies and municipalities spent money for improvements after the publication of the Regulations of the Earth Current Commission. Exact information was not available regarding the number of places where changes had been made, but the best information indicated that the number was between 20 and 30. Of these, about 100,000 marks each was spent in Danzig, Strassburg and Erfurt, re-arranging the resistances in existing return conductors, and Dresden was engaged in insulating the existing bare conductors, and generally, the most important cities were rapidly improving their return circuit conditions.

The present conditions in Germany are considered satisfactory where the electric railways have conformed to the Commission Regulations, or where conditions were already equally good; in other cases the conditions are considered to be unsatisfactory. No cases of extensive damage to cable sheaths were found.

Italy. Very little damage, if any, is known in Italy, and the conditions are said to be satisfactory. This favorable report is based on the absence of complaints.

France. Outside of Paris, there is little damage caused by tramway systems, which generally observe a one volt per kilometer rail drop limit, contained in regulations issued by the Ministry of Public Works. No adequate or complete tests have been made in France, although some testing has been done in Paris following the development of trouble.

In Paris, 60 to 70 cases of damage to pipes have been found in a year, and the actual minimum cost of repairs was estimated to be 60,000 francs; however, it was held that the paramount consideration was the danger to security of service, since nearly all cases caused losses in buildings, although there were no explosions.

At least 30 to 35 per cent of the total number of cases reported were due to re-arrangement of the Edison two-wire and three-wire mains; such troubles are local and temporary, while in other cases the troubles are persistent.

A very considerable amount of damage in Paris is due to the "Metropolitan" subway system, which claims exemption from the one-volt per km. rule, not being a tramway system. With this exception, conditions in France are said to be generally satisfactory.

England. Considerable damage is said to have occurred in the early days of electric traction in England, although such damage was apparently insignificant compared to conditions familiar in America. Practically no damage has occurred in recent years, and certainly no extensive damage. Two or three cases, local in character and of small extent, have occurred in localities where the Board of Trade regulations were complied with.

In England there is very little good evidence in the way of tests, and the general statements of immunity are based on the absence of trouble. The Post Office and the South Metropolitan Gas Company (London) both make systematic tests and find no trouble, with the exception that the Post Office has from time to time encountered difficulties due to stray currents, which were however generally quite local in character.

While it is generally stated in England that there is little actual damage to piping systems, and that the problem is not an important issue with the owners of gas piping systems, there is considerable feeling among the privately owned gas companies that they are not adequately protected by the Board of Trade Regulations, since they cannot recover damages in case corrosion occurs where the Regulations are complied with. This has led to numerous applications to Parliament for special clauses in Acts granting powers to electric railway undertakings; most of these have been refused, but some have been granted.

It is generally admitted that the Board of Trade Regulations, as originally drawn, were empirical, and that they might be remodelled with advantage. but since the only feature of the regulations actually rigidly enforced: namely, the limit for overall rail drop, results in substantial immunity, the great difficulty attending revision does not seem justified.

83. Protective Measures in Vogue.

FEEDERS.

Germany. Insulated return feeders are used almost universally in Germany. In Berlin and Hamburg these return feeders are of the same number and size as the positive feeders, but generally in other towns the return feeders are of smaller cross-section. Separate feeders are generally used, but not exclusively, as feeders with resistance taps are used in some cases. Formerly there were cases of feeders tapping at several points, but important cases have been corrected by the insertion of resistances. (The distinction between copper which merely parallels the rails, and feeders intended to maintain equi-potential points in the rail net-work, is clearly understood in Germany).

Negative boosters are used in several cases, but the general practice is not to use them. The tramway in Danzig, operated by a private company, and having a maximum load of 600 kw., has used boosters since 1906.

Return feeder systems are carefully calculated in recent installations; the same grade of insulation is generally provided for both positive and negative feeders. No design data for feeder resistances were obtained.

England. Insulated return feeders are used in England, wherever return feeders are necessary to bring the rail drop within the B.O.T. regulations Separate feeders are generally used. (As in Germany, the feeders are intended to maintain the rail taps at the same potential throughout the system).

Negative boosters are more extensively used than in Germany. They are very commonly used in the larger systems, although in one large city their use was abandoned after they had been in operation for some time. They are considered more economical than resistances in the return feeders, and also to provide better regulation where the load centers shift.

Return feeder systems are only calculated in the larger, well supervised systems, elsewhere they are installed on "cut-and-try" methods. The same grade of insulation is usually provided for both positive and negative feeders.

Italy. Return feeders are not used for tramways in Italy.

France. Insulated return feeders are used for the conduit tramways in Paris, but little elsewhere. Most systems have but one feeding point to the rails. Boosters are very little used, the only system found to be equipped with boosters was that of the Cie. des Tramways de Paris et du Dept. de la Seine.

VOLTAGE AND CURRENT CONDITIONS.

Germany. Where return circuits have not been remodelled in accordance with the Commission Regulations, overall voltage limits vary greatly, but in the majority of cases they are between 5 and 10 volts. Other systems will be from 2 to 5 volts. Negative feeders are designed for equal drop.

England. Overall rail drops for tramways in England are generally very much lower than the B.O.T. requirement, averaging probably 2.5 to 3 volts, with the exception of occasional drops, which may be as high as 15 or 20 volts, due to extraordinary traffic at foot-ball matches, etc. The railways probably have higher overall voltages than the tramways. Glasgow, which voluntarily adopted a 2 volt rail drop limit, Manchester, and other large towns, have extraordinarily low rail drops. Electrolysis conditions throughout the United Kingdom are generally said to be satisfactory, although some private gas companies do not agree to this. Potential differences between pipes and rails are said to be generally less than 1 volt.

Negative feeders are designed for equal drop.

France. It is stated that the tramways in France generally endeavor to observe the 1 volt per km. limit. Potential differences between pipes and rails rarely exceed 1 volt (However we observed a 6 volt potential in Paris).

MISCELLANEOUS PROTECTIVE MEASURES.

Drainage System. Electrical drainage was formerly applied in one or two cases in Germany, notably in Aachen, but it was abandoned on account of damage produced by it, first, due to joint corrosion, and second, damage to other underground structures. It is condemned by the engineers of the Earth Current Commission.

Electrical drainage is not employed in Italy or France.

In England, it is not approved as a general measure to afford relief from stray current, although there are a few special instances of its application to the Railway Company's own lead covered cables, where the common practice is to bond to the rails at many points. One engineer thought that it might be applied where currents were small, except to gas pipes on account of the danger from sparking, he also thought that it would be undesirable in America where large currents are carried.

Negative Trolley or Periodic Reversal. The trolley wire was originally made negative in Nürnberg, and in St. Gall, Switzerland, but not periodically reversed. The scheme has been abandoned in both places.

This connection has not been used for tramways in Italy, France or England.

Three-Wire System. The three wire system has been applied to electric railways in a few cases in Germany. In each case the distribution of load between polarities was by districts, that is, certain entire sections will have the trolley wire positive, and others will have the trolley wire negative. Under these conditions the systems may become considerably unbalanced.

In France, the Nord-Sud Chemin de Fer employs a three-wire system with two motors per car, positive and negative, the running rails acting as a grounded neutral.

In England the three-wire system has not been applied to tramways. The City and South London Underground Railway employs it, but this will be discontinued following consolidation with other systems.

Average Feeding Distances. In England, the average feeding distances are said to be from 2 to 3 miles.

Joints in Cast-Iron Mains. Cast-iron pipes in England and Germany are generally of the lead calked bell and spigot type In Germany flanged joints are frequently used for special fittings, valves, T's and hydrant taps for water mains. Cast-iron pipes are little used in France; pipe joints are either lead calked bell and spigot, or in large pipes flanged with rubber gaskets. Insulating joints are not used, except that in England it is said that they are occasionally used for water pipes in very special cases.

Insulating Coverings. In Germany it is held that insulating coverings do not afford protection against electrolysis, as their effect is merely to concentrate escaping stray currents, since perfect coverings cannot be maintained. They should only be used where protection against chemical corrosion is desired, due to the character of the soil.

In France, gas engineers stated that insulating coverings were being studied, but it was not believed that they would prove practicable.

In England, insulating coverings are not considered good protection against stray railway currents. High pressure gas pipes have been covered with pitch canvas, and the London Water Board pipes are provided with an asphalt dip coating, but more as protection against chemical corrosion.

Insulating Joints in Telephone Cables. Not used in Germany or England.

Double Trolley. The double trolley system is not in general use in any of the countries visited. One or two very special cases near Laboratories in Germany, the district within 2 or 3 miles of the Greenwich Observatory, and some conduit tramways of the London County Council System, were the only cases noted. The double trolley is also used in connection with a few miles of rail-less trolley in England.

Corrosive Effects of Soil. In Germany the possibility of chemical corrosion (that is, corrosion without an external supply of electricity) is recognized, and distinction is made between such corrosion and that produced by stray currents. Pipe corrosion has actually been found under conditions where it could not have been produced by stray currents. The resistance of soil is said to vary from 1 ohm to 2000 ohms per cubic meter, averaging about 100 ohms per cubic meter.

No definite information was obtained in England regarding the corrosive properties of soil, but it was stated that chemical corrosion was known to occur. Such corrosion does not, however, produce acute conditions, as in electrolysis; it is more like ordinary oxidation.

Effect of Roadbed Construction on Leakage Current. The authorities consulted in Germany were of the opinion that the road-bed constructions used did not effect a reduction of leakage from the tracks. A similar opinion was held in England. (See Fig. 10-13).

Rail-Weights. In Germany the common rail weights are 50-60 Kg. per meter for tramways, and 30-40 Kg. per meter for interurban lines. In France the ordinary rail-weights are 46 to 51 Kg. per meter. In England rail-weights vary from 70 to 100 lbs. per yard, in the majority of cases. (See Fig. 14).

Welded Rail-Joints. In Germany Thermit welds are used to some extent, they are becoming more common. In France the rails of the System Cie. de Omnibus Thomson-Houston, are welded.

In England Thermit welds have been very extensively used, giving good results electrically, but having short life due to mechanical weakness where traffic is heavy. A type of electrically welded continuous rail, very extensively used in Leeds, and to an increasing extent in Manchester and Glasgow, is giving excellent results, being mechanically strong and providing good electrical conductivity.

Rail-bonds. Solid copper pin type bonds, usually 1 meter long, are most commonly used in Germany, and also in France. The Metropolitan System in Paris places the bonds under the base flange of the rail.

In England, solid copper pin type bonds, protected bonds inside of fish plates, and other types familiar in America, are generally used. (See Fig. 15).

Cross-bonds. In Germany, cross-bonds are used about every 10 rails, *i.e.*, every 100 meters. In France, cross-bonds are placed every 50-100 meters, they have the same area as the rail-bonds. In England cross-bonds are placed generally every 40 yards, they have the same area as the rail-bonds. (See Fig. 16).

Depth of Pipes etc. Below Surface. In Germany, gas pipes are generally laid 0.8-1. meter, and water pipes 1-1.5 meters, below the surface. In France, gas pipes are laid where possible 0.6 meter below the surface, L.T. cables 0.7 meter, and H.T. cables 1.3 meters. In England 1 foot is said to be dangerous; 2 feet was given by one authority as an average and 2.5 to 5 feet by another. In all cases the above depths are only typical, the practice varies widely.

Mains on Both Sides of Streets. In Germany, France and England, mains are laid on both sides of principal streets, or streets wider than 14 meters (Paris) or in streets with wood or asphalt pavements, and generally in the larger towns. In narrow streets or in unimportant places, one main is used.

84. Economic Aspects of the Electrolysis Problem. About 40 per cent of the electric railway systems in Germany, and about 70 per cent in England, are municipally owned. In Germany one authority thought that municipalities were more ready than private companies to spend money for the purpose of improving their return circuits, but in England it was thought that there was no difference in this respect.

Opinions differed in Germany as to whether or not the prevailing regulations constituted a financial hardship. In England, the Board of Trade regulations are nowhere considered a hardship, and when inquiry was made as to whether the existing regulations had retarded the development of electric railways, the authorities consulted uniformly stated that this was not the case. It appears that in fact a saturation point has been reached, and busses are being used where tramways would not pay. Traffic conditions are said to be quite as heavy in England as in the United States. Only one authority in England ventured an estimate of the average load factor for English electric railway systems, he estimated it to be 35 per cent.

There is very little overhead feeder line construction in Germany, and almost none in England.

85. Regulations and Tests. The German Earth Current Commission Regulations only attain the force of law when incorporated in the contracts between civil authorities and the railroad companies, or, as in the case of many cities, where it is provided that new work be done in accordance with "existing technical standards." The Commission regulations are being generally incorporated in contracts for new enterprises or extensions. Also, other undertakings not subject to its provisions are changing over voluntarily for reasons of policy or economy, or as the result of compromise to avoid litigation; this is said to be the case in 30 or 40 important towns.

So far as could be ascertained, no local ordinances exist in Germany regarding electrolysis. In England, there are no local ordinances which have the effect of modifying the Board of Trade regulations. Certain gas companies have obtained special statutory orders, fixing the responsibility for damage, but these do not modify the Board of Trade regulations.

In applying the Earth Current Commission Regulations in Germany, the term "average schedule traffic" is interpreted to mean the average for the entire period of operation which is usually 18 or 19 hours per day. If the measurements are not actually taken over the entire period, they are corrected to obtain a figure corresponding to this average.

In England, measurements are based on an average for about 20 minutes at peak load. The "average" is obtained as the mean between the average of the maxima during this period, disregarding unusually high swings, and the actual average of all measurements. This quantity is usually obtained in practice from inspection of recording instrument charts.

The British Board of Trade makes inspections on its own initiative, because it is responsible for its rules, which have substantially the force of law; they also investigate complaints. There are no regular inspections, on account of the lack of a proper appropriation; most of its information is obtained by means of circular returns, provided for in the Regulations. The latest call for a return was issued in 1906.

In Germany, permanent means for measuring overall potentials are very generally provided, but the methods of doing this vary widely. Pilot wires are usually provided for new installations in France.

In England, pilot wires are universally used in connection with recording instruments. The practice varies widely, but the most common method employs 14 or 16 gauge wires laid with the main cables, and extended beyond them.

Bond testing is generally done in Germany on some systematic basis, more often annually, but in some large systems semi-annually. The bond testing devices are generally of the three contact type with differential galvanometer. Some of these are said to be undesirable on account of the form of the contact, others because the rail joint points span too short a length, or on account of the type of galvanometer employed, etc. In England, it is stated that there is practically no systematic bond testing except in the large, well supervised systems.

I. GENERAL REMARKS

86. Germany. Where municipalities own the water, gas and street railway systems, they may prefer to assume the cost of damage rather than making larger expenditure for protection of their pipes. There are cases in dispute pending in Essen and Aachen. In Aachen the drainage system was formerly used, but gave trouble; changes are under study or under way.

Recently the case of Mansfeld was decided against the gas company as the railway existed before the gas plant.

Hamburg, prior to the forming of the commission, installed return insulated feeders which gave valuable information in guiding the recommendations of the commission.

Strassburg found in summer 50 % greater leakage than in winter when measurements were made in cold weather and the ground frozen. In snow storms, however, the leakage was increased as the cars were using more current.

The Prussian Law protects railway companies against suits for damages caused by stray currents whenever the pipe owning concerns did not apply for protection against these possible damages before the original franchise to the Railway Company was granted.

Similar laws apply in other States.

When the municipality assumes the operation of a railway it does not assume responsibility to protect the pipe owning companies against damages due to stray currents.

87. France. In Paris pipes for water are located in sewers and therefore remote from trouble.

Telephone cable troubles are few in Paris. In the suburbs all underground pipe systems are more or less affected.

Twenty suits are now in litigation between the gas companies and the railways.

J. STATISTICAL—OPERATING—STRUCTURAL AND TECHNICAL DATA.

TABLE 1.

88. Magnitude of Electric Railway Undertakings in German Empire and United Kingdom.

	German Empire 1911	United Kingdom 1912
Number of undertakings	258	262
Miles of single track	4,920	4,202
No. of cars of all kinds	26,078	12,860
Capital expended £	54,354,625	77,087,944
Car miles	430,512,031	326,688,674
No. of passengers	2,631,892,678	3,145,805,137
Gross income £	13,237,024	14,593,052

TABLE 2.

89. Tramways not Operated by Electricity.

	Miles of single track.			
	Horse	Steam locomotive	Cable	Petrol motors, etc.
German Empire, 1911.........	45.1	49.8	4.1	10.0
United Kingdom.1912.........	38.7	42.3	50.1	4.8

TABLE 3.

90. Ownership of Electric Railway Undertakings

A—German Empire, 1911.

	Private corporations	Local authorities	Public ownership operated by private corporations
No. of undertakings............	112	110	36
Miles of single track...........	2,711	1,646	563
No. of cars of all kinds.........	16,390	7,756	1,932
Capital expended £............	32,685,120	16,232,025	5,437,480
Car miles.....................	260,729,075	134,466,975	35,315,981
No. of passengers.............	1,519,571,662	890,127,262	213,193,754
Gross income £................	8,095,757	4,118,873	1,022,394

B—United Kingdom, 1912.

	Private corporations	Local authorities
No. of undertakings...........	94	168
Miles of single track...........	1,115	3,078
No. of cars of all kinds..........	3,444	9,416
Capital expended £............	22,648,596	54,439,348
Car miles.....................	81,191,368	245,497,306
No. of passengers..............	621,546,806	2,524,358,331
Gross income £................	3,534,873	11,058,179

TABLE 4.

91. Statistics of Tramways in Large Cities.

A—German Empire.

	Max. load kw.		Avg. car miles per diem		Avg. pass. per diem		Annual gross Income-marks	
	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per capita.
Hamburg (935,000)	..	..	91,450	981	460,000	4940	12,208,781	12.97
Leipzig (590,000)	2,145	36.5	59,910	1020	328,500	6590	11,129,578	18.95
Dresden (550,000)	3,300	60.3	59,410	1085	345,800	6320	12,324,054	22.55
Dusseldorf (360,000)	1,386	38.8	27,040	756	183,000	5120	5,524,714	15.45
Nürnberg (330,000)	880	26.5	18,860	569	108,600	3280	3,543,810	10.69
AVERAGE.	..	40.5	....	882	..	5050	....	M16.12 $ 3.85

B—United Kingdom.

	Max. load kw.		Avg. car miles per diem		Avg. pass. per diem		Annual gross Income-pounds	
	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per capita.
Manchester 1,250,000)	11,000	88	51,400	411	510,400	4082	887,647	0.710
Glasgow (1,150,000)	11,500	100.	63,950	556	854,000	7422	1,070,175	0.932
Birmingham (900,000)	..	..	36,000	400	368,000	4088	581,566	0.646
Leeds (450,000)	4,500	100.	24,100	536	245,800	5460	411,531	0.914
Dublin (390,000)	4,500	115.4	19,650	504	147,700	3790	293,748	0.752
AVERAGE.	..	100.9	....	481	....	4968	....	£ 0 791 $ 3 84

TABLE 5.

92. Statistics of Tramways in Small Cities.

A—German Empire.

	Max. load kw.		Avg. car miles per diem		Avg. pass. per diem		Annual gross Income-marks	
	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per capita.
Cassel (153,078)	469	30.6	6215	406	38,550	2516	1,474,199	9.62
Braunschweig (143,534)	466	32.5	7090	494	33,100	2306	1,205,577	8.40
Erfurt (111,461)	301	27.3	3580	321	19,010	1708	637,792	5.72
Freiburg (83,328)	165	19.8	2742	329	18,860	2264	664,625	7.98
Solingen (50,540)	250	49.5	3730	738	23,250	1600	973,240	19.25
AVERAGE........	..	32.0	....	458	....	2679	....	M10.20 $ 2.15

B—United Kingdom.

	Max. load kw.		Avg. car miles per diem		Avg. pass. per diem		Annual gross Income-pounds	
	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per 10,000 Popul.	Actual	Per capita.
Brighton H. (173,000)	995	57.5	3165	183	31,000	1792	53,748	0.311
Dundee (168,600)	1700	101.0	3725	221	48,550	2880	65,045	0.386
Preston (121,000)	600	49.6	2660	220	26,200	2166	43,270	0.358
Coventry (91,000)	750	77.0	2720	299	20,900	2297	39,153	0.430
Burton T. (50,000)	375	74.4	1240	246	9140	1815	16,897	0.316
AVERAGE........	..	72.0	....	234	....	2190	....	£ 0.360 $ 1.75

TABLE 6.
93. Rail Bonding.
United Kingdom.

	No. of undertakings	Miles of single track	Per cent of total (miles)
Copper Bonds.			
Solid copper, type not specified	46	560.	....
Flexible " " " "	9	176.	....
Crown—3/0 and 4/0	20	321.	....
Neptune 4/0	19	229.2	....
Chicago	8	71.3	....
Forest City	5	37.2	....
Misc. and type not specified	15	406.8	....
TOTAL, copper bonds only	122	1801.5	47.3%
Welded Rails, Etc.			
Continuous rails, type not specified	1	17.	....
Yalk cast weld	1	20.	....
Thermit	3	61.6	....
" and Yalk	1	15.9	....
" and Tudor	1	28.	....
" and Oxy-Acetylene	1	18	....
TOTAL, entirely welded	8	160.5	4.2%
Partially Welded:			
Copper and Thermit	31	1312.4	....
" " other welded joints	5	377.3	
TOTAL, partially welded	36	1689.7	44.3%
Plastic Bonds, Etc.			
Plastic bonds and copper	3	147.5	....
" " " Thermit	1	12.3	....
	4	159.8	4.2%

TABLE 7.

94. Use of Negative Boosters.

United Kingdom.

	Number	Miles of single track
Total number of undertakings...........................	183	3835.
Number of undertakings using negative boosters	39	1152.
Per cent using negative boosters.......................	21.3%	30. %

Relation between Booster Capacity and Plant Capacity

Average, for 25 cases: Booster Capacity—3.9% of plant capacity.

Highest— 9 % for plant of 500 kw. capacity
12 % " " " 800 " "
Lowest —0.8 % " " " 5725 " "
0 9 % " " " 3500 " "

TABLE 8.

95. Distribution Systems for Tramway Feeders.

United Kingdom.

	No. of undertakings	Miles of single track
Solid system, all types..............................	80	1888.2
Conduit " " "	63	1839.2
Solid and conduit	21	626 1
Overhead, wholly or partly	6	40 9
	170	4394 9
Not reported..........................	11	
	181	

STREET AND ROAD TRAMWAYS, AND LIGHT RAILWAYS
(Board of Trade Statistical Report, 1913)

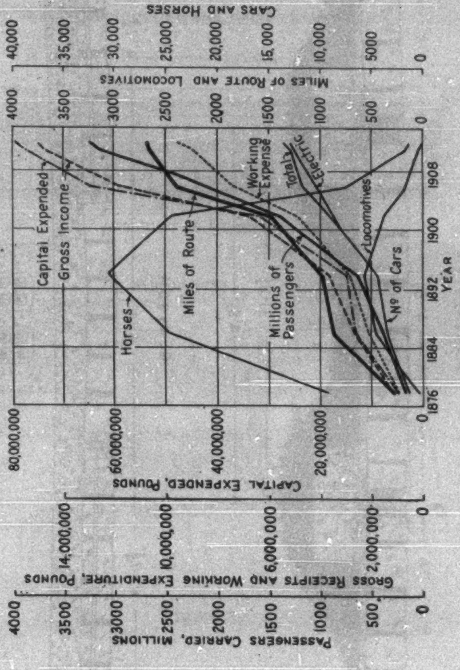
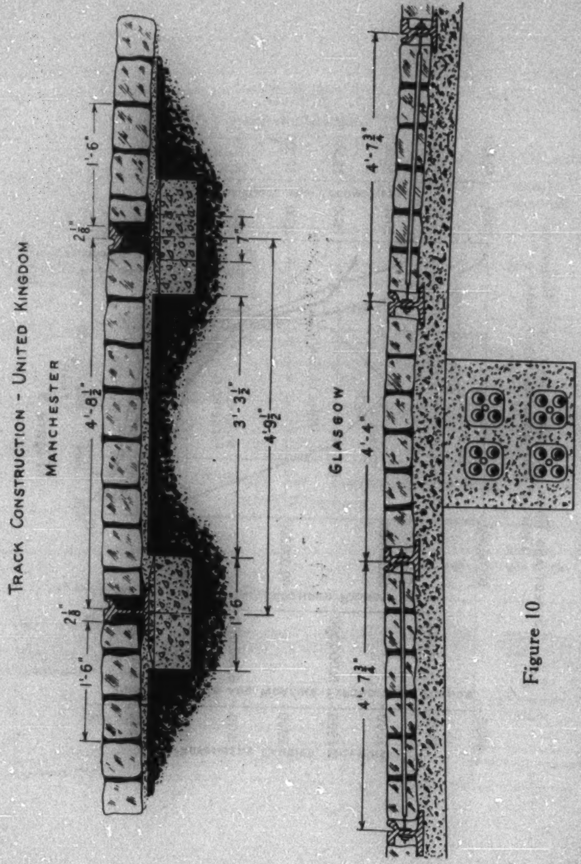


Figure 9

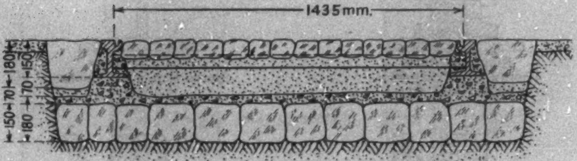


TRACK CONSTRUCTION - UNITED KINGDOM

MANCHESTER
1'-6"
2⅛"
4'-8½"
2⅛"
1'-6"
7"
3'-3½"
4'-9½"
1'-6"
GLASGOW
4'-7¾"
4'-4"
4'-7¾"

Figure 10

TRACK CONSTRUCTION AND RAILS - GERMANY


1435mm.
180
150
170
170
150
180

Typical Construction for paved street

STRASSBURG
Haarman 3 piece Rail, and foot plate

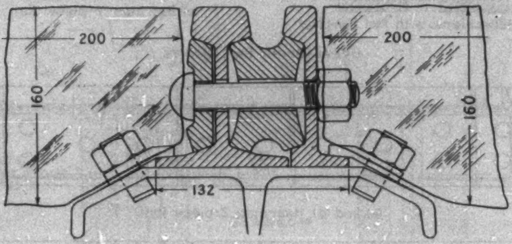
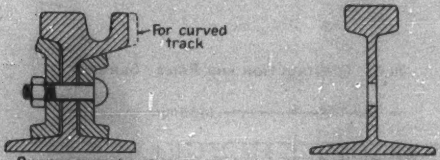

200
200
160
160
132

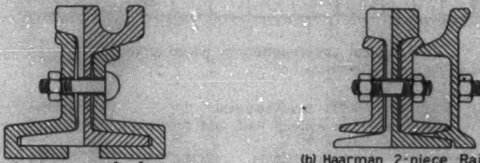
Figure 11

GERMAN TRAMWAY RAILS



RILLENSCHIENE
Phönix Profil I and Ia
42.8 and 45.7 Kg/m

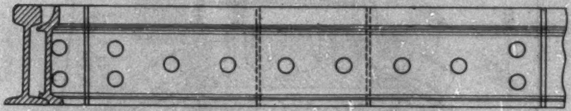
VIGNOLSCHIENE
Special profile for Tramway



(a) Rillenschiene with "foot" fish-plate

(b) Haarman 2-piece Rail

OVERLAPPING RAIL JOINTS



(c) and (d) Haarman 2-piece Rail

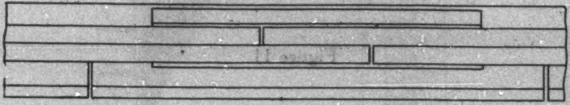
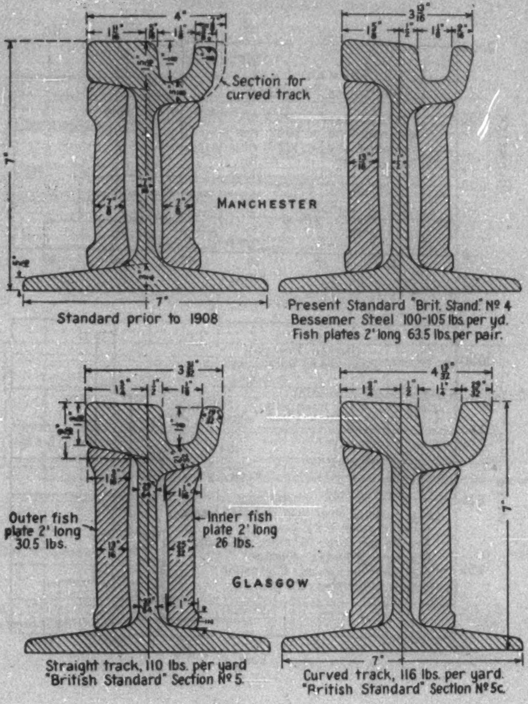


Figure 12

BRITISH TRAMWAY RAILS


4"
Section for curved track
7"
MANCHESTER
7"
3 13/16"
GLASGOW
3 31/32"
4 13/32"
7"
Outer fish plate 2' long 30.5 lbs.
Inner fish plate 2' long 26 lbs.
7"

Standard prior to 1908

Present Standard "Brit. Stand." Nº 4
Bessemer Steel 100-105 lbs. per yd.
Fish plates 2' long 63.5 lbs. per pair.

Straight track, 110 lbs. per yard
"British Standard" Section Nº 5.

Curved track, 116 lbs. per yard.
"British Standard" Section Nº 5c.

Figure 13

RAIL WEIGHT DATA

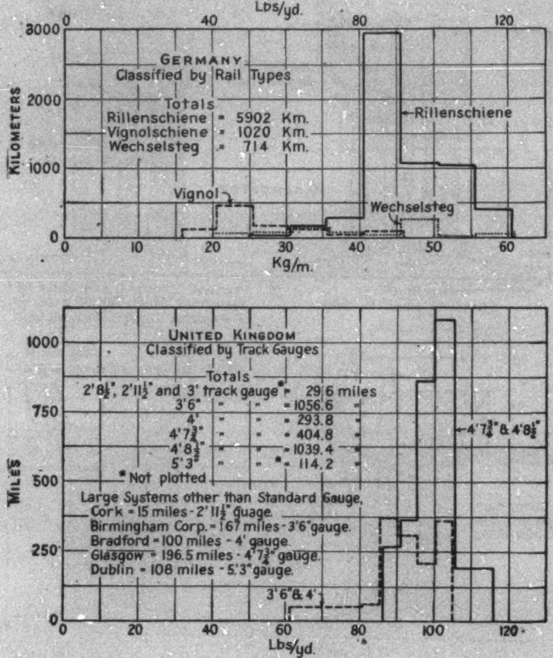


Figure 14

TYPICAL RAIL BONDS - UNITED KINGDOM

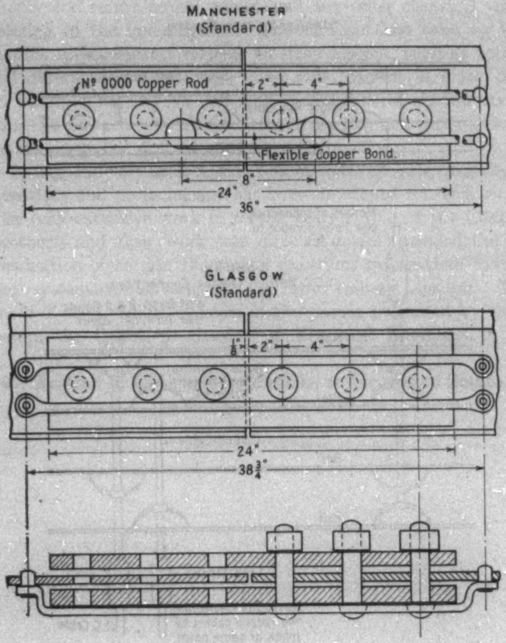

MANCHESTER
(Standard)
Nº 0000 Copper Rod
2"
4"
Flexible Copper Bond.
8"
24"
36"
GLASGOW
(Standard)
$\frac{1}{8}$"
2"
4"
24"
38$\frac{3}{4}$"

Figure 15

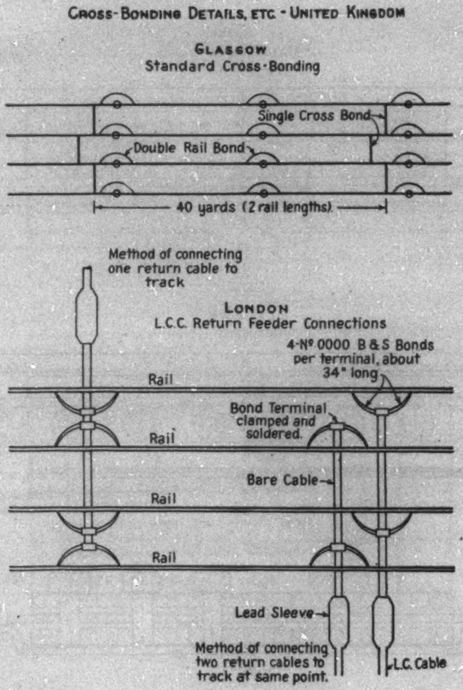

CROSS-BONDING DETAILS, ETC. - UNITED KINGDOM
GLASGOW
Standard Cross-Bonding
Single Cross Bond
Double Rail Bond
40 yards (2 rail lengths)
Method of connecting one return cable to track
LONDON
L.C.C. Return Feeder Connections
4-Nº 0000 B & S Bonds per terminal, about 34" long
Rail
Bond Terminal clamped and soldered.
Rail
Bare Cable
Rail
Rail
Lead Sleeve
Method of connecting two return cables to track at same point.
L.C. Cable

Figure 16

96. Electrolysis Testing Methods. The surveys made by the engineers of the Earth Current Commission of Germany are systematically planned. They start with a general investigation of geological conditions, the character of the soil, ground water, and so forth, continuing with a general survey of the present condition of the railway property, including distribution of load, track and rail resistance, location and loading of supply and return circuit cables, and any other electrical data relating to the investigation. The surveys then take up the specific measurements relating to stray current, such as potential differences between pipes and rails, current in pipes, and so forth. The surveys conclude generally with recommendations for betterments where such are needed, and often include estimates of the cost of such improvements.

In England very little testing is done to investigate electrolysis questions and no technique has been developed for such work. The only extensive work in recent years is that of the Cunliffe brothers, and their work was directed mainly toward the investigation of certain theoretical questions rather than toward the systematic investigation of any railway system. The work of the Cunliffes appears in two papers presented by them before the British Institution of Electrical Engineers.

97. Abstract of Laws and Regulations or Recognized Standards in European Countries.

(See next page.)

Country	England	France	Germany	Italy	Spain.
Nature of Regulations,	Board of Trade Regulations. Original issue March 1894, last revision Sept. 1912.	Ministerial Decree of Mar. 21, 1911.	No laws, but the Recommendations of the German Earth Current Commission are recognized as Standards.	No laws or Municipal Regulations	Law of Mar. 23, 1900.
Maximum Rail Drop, (See text as to how determined in different countries)	7 volts total.	1 volt per km.	2.5 volts total in central district; 1.0 volt per km. in outer districts.		7 volts total.
Return Feeders,	May be uninsulated unless drop exceeds 7 volts.	Must be insulated.	Must be insulated.		
Rail Bonds: Tested,		Periodically and record kept.	Yearly		
Resistance not to exceed		10 meters of rail	10 meters of rail		Section must exceed 100 sq. mm. per rail.
Connections to pipes,	For test purposes may connect to water mains of 3 in. or more diameter with owner's permission.		Prohibited.		
Pilot wires,		Must be provided.	To be provided.		

L. MISCELLANEOUS NOTES.

98. Plan of German Earth Current Commission Reports. In abstracting these reports we have selected at random characteristic studies which would illustrate the method pursued in the investigations. We have not made any attempt at all to select studies for direct comparison with any specific American condition. In interpreting these results, the above qualifications should, therefore, be kept in mind.

The reports are quite uniform in character and contain in general the following data:

I. Maps showing the location and extent of the tramway, water pipe and gas pipe systems, location of the generating station or stations, points of connection of the supply and return feeders.

II. Soil—kind (clay, sand, loam, etc.) moisture content, chemical composition, resistance per cubic meter.

III. Pavements—(in some cases only).

IV. Piping systems—both water and gas pipes. Total length, diameter, material, age, depth below surface, kind of joints, resistance of pipe only and of pipe including joints.

V. Tramway system.

(a) General details of ownership and operation, car schedule, maximum and average loads.

(b) Track and rails—total miles of single and double tracks, gauge, rail profile and cross section, standard length, resistance of rail alone and including bonds.

(c) Rail bonds and cross bonds, type, cross section, per cent increase in rail resistance caused by bonds.

(d) Feeders, both supply and return feeders—length each, cross section, total weight of copper, current—maximum and average, return feeders bare or insulated and with or without regulating resistance.

VI. Tests.

(a) Voltage between pipes and rails, maximum, minimum and average, with polarity, determined at numerous points on the system.

(b) Voltage drop per kilometer on pipes and on rails and calculated current flowing on pipes.

(c) Determination by means of telephone wires of the relative potential of various points on the piping and on the rail systems.

VII. Excavations in likely places to determine the existence and extent of the electrolytic damage.

VIII. Plates accompany the reports, giving graphically many of the above data, frequently on transparent paper so that when placed over the city map the details of streets, railroads, etc. can be observed.

Reasoning from the data contained in the body of the report, recommendations are made for improving conditions, sometimes accompanied by an estimate of cost. In some cases a supplementary report is made which shows the conditions after the changes recommended had been made, in whole or in part.

99. General Comments on Reports. The electrolysis troubles in all cases were confined to a few localities, and in no case was the yearly cost of repairs of such amount that, on the surface, would justify large expenditure of money for improvements. The Commission, however, while recognizing the importance of the financial aspect of the problem, still recommended the adoption of the relatively expensive remedies for the reason they state "that the repairs will certainly become more frequent with lapse of time, and besides the increased expense so caused, there is the liability of service interruption, disturbance of traffic, pavement replacement and even danger of explosion to be considered."

V. BIBLIOGRAPHY

This committee has made a complete search of the American literature on the subject of electrolysis, but in compiling the following bibliography no attempt has been made to list this literature in its entirety. This bibliography may be considered a selected list of such contributions to the subject known to the committee, as, in its opinion, are of permanent value.

Bureau of Standards Publications: The following Technologic Papers upon electrolysis have been published by the Bureau of Standards at Washington, D. C.

No. 15. Surface Insulation of Pipes as a Means of Preventing Electrolysis.
No. 18. Electrolysis in Concrete.
No. 25. Electrolytic Corrosion of Iron in Soils.
No. 26. Earth Resistance and its Relation to Electrolysis of Underground Structures.
No. 27. Special Studies in Electrolysis Mitigation.
No. 28. Methods of Making Electrolysis Surveys.
No. 32. Special Studies in Electrolysis Mitigation, No. 2, Electrolysis from Electric Railway Currents and its Prevention—Experimental Test on a System of Insulated Negative Feeders in St. Louis.
No. 52. Electrolysis and Its Mitigation.
No. 54. Special Studies in Electrolysis Mitigation, No. 3. A Report on Conditions in Springfield, Ohio, with Insulated Feeder System Installed.
No. 55. Special Studies in Electrolysis Mitigation in Elyria, Ohio, with Recommendations for Mitigation.
No. 62. Modern Practice in the Construction and Maintenance of Rail Joints and Bonds in Electric Railways.
No. 63. Leakage of Current from Electric Railways.
No. 72. Influence of Frequency of Alternating or Infrequently Reversed Current on Electrolytic Corrosion.
No. 75. Data on Track Leakage.

Deiser, George F. "The Law Relating to Conflicting Uses of Electricity and Electrolysis," T. & J. W. Johnson Co., Philadelphia, Pa., 1911.

Farnham, Isiah H. "Destructive Effect of Electric Currents on Subterranean Metal Pipes," *Trans.* A. I. E. E., 1894.

This paper probably covers the first investigation undertaken of real scientific value. The discussion of the paper is also important and interesting.

"Means for Preventing Electrolysis of Buried Metal Pipes," *Cassiers Magazine,* August, 1895.

This article is of particular interest, in that it shows that at a very early date the value of the insulated negative feeder system as a means of mitigating electrolysis was recognized.

Ganz, Albert F. "Electrolytic Corrosion of Iron by Direct Current in Street Soils," *Trans.* A. I. E. E., Vol. XXXI, p. 1167, 1912.

This paper gives the results of a laboratory investigation of considerable scientific value and interest.

"Electrolysis from Stray Electric Currents," *Proc. New England Association of Gas Engineers,* 1913.

This paper treats the subject in a popular, but nevertheless scientifically correct manner, and leads to the conclusion that the insulated negative feeder system is the logical one to employ for the purpose of mitigating electrolysis.

"Effects of Electrolysis on Engineering Structures," Trans. Inter. Eng. Congress, San Francisco, Cal., 1915.

This paper gives a review of electrolysis conditions and of mitigating methods in America with a brief statement of the electrolysis situation in Europe.

Haber, F., and Goldschmidt, F. "Der Anodische Angriff des Eisens Durch Vagabundierende Strome im Erdreich und die Passivitat des Eisens." (The Corrosion of Iron by Stray Currents in the Ground and the Passivity of Iron.) *Zeitschrift fur Electrochemie,* January 26, 1906. Breslau.

A paper of considerable scientific value, particularly with respect to the electrochemistry of the subject. In so far as is known no English translation exists.

Harper, Robert B. "Comparative Values of Various Coatings and Coverings for the Prevention of Soil and Electrolytic

Corrosion of Iron Pipe," *Proc. Illinois Gas Association*. Vol. 5, 1909.

A paper based upon a rather elaborate series of tests carried out in a thoroughly scientific manner on many coatings and coverings, leading to the conclusion that no coatings or coverings are of permanent value in positive areas. Of all coatings investigated, dips of coal tar pitch applied hot, were found to be best. Paints were found to be practically useless.

Hayden, J. L. R. "Alternating-Current Electrolysis," *Trans.* A. I. E. E., 1907. Vol. 26, Part I.

A report of a laboratory investigation tending to show that alternating current electrolysis is small as compared with direct current electrolysis. The tests also bring out the inhibiting effect of the superposition of a small direct current.

Jackson, Dugald C. "Corrosion of Iron Pipes by Action of Electric Railway Currents." *Journal of Association of Engineering Societies*, September, 1894.

An account of some early laboratory investigations carried out at the University of Wisconsin, in which it was definitely proven that corrosion due to electrolysis could take place at very low voltages—considerably lower voltages than are required to decompose water.

Michalke, Carl. "Stray Currents from Electric Railways." Translated and edited by Otis Allen Kenyon, McGraw Publishing Company, New York City, 1906.

A relatively non-mathematical, though scientific and valuable treatment of the subject.

Rhodes, George I. "Some Theoretical Notes on the Reduction of Earth Currents from Electric Railway Systems, by Means of Negative Feeders." *Trans*. A. I. E. E., Vol. XXVI, p. 247, 1907.

A mathematical paper showing quantitatively the difference in effectiveness of copper paralleling the rails and insulated negative feeders in reducing stray currents.

Schaffer, Guy F. "Corrosion of Iron Embedded in Concrete." *Engineering Record*, July 30, 1910.

This is a report of a series of tests made at the Massachusetts

Institute of Technology, carried out with the view of obtaining some data on the effect of currents of low potential on steel embedded in concrete. The study included the effect on steel in both the stressed and unstressed condition, also the effect of setting cement on paint films. It was shown (a), that concrete does not act as an insulator; (b), that iron under stress does not go into solution as rapidly as unstressed iron; and (c), that the paints used to-day for structural work embedded in concrete do not fulfill the conditions of proper protection from electrolytic action, and it is doubtful whether they are of use for protection in any sense after a lapse of some months.

Sever, George F. "Electrolysis of Underground Conductors." *Trans. International Electrical Congress*, St. Louis, Vol. 3, p. 666, 1904.

This is a summary in tabular form, consisting of street railway practice, municipal reports, ordinances and letters in force in the United States at the time the report was prepared, 1904. The discussion which followed the presentation of this report is of interest.

Stone, Charles A. and Howard C. Forbes. "Electrolysis of Water Pipes." *New England Water Works Association*, Vol. 9, 1894-95.

This is the report of the results of an investigation of electrolysis conditions in Boston. It is one of the best early papers on the subject. The discussion of this paper is interesting.

Topical Discussion on Electrolysis. *Proc. New England Water Works Association*, Vol. XX, 1905.

This is the report of a discussion entered into by various New England Water Works superintendents. Several phases of the discussion are instructive.

VI. APPENDICES.

100. Resistance of Standard Cast Iron Pipe.

Note: The values given in this table are for one assumed specific resistance for cast iron, wrought iron and steel, respectively. For exceedingly accurate work, measures should be taken to determine the actual specific resistance of the metal under test. Experience has shown that this may vary widely from that assumed in the tables; in other words, the table values can only be used for approximate results unless definite information is at hand as to the specific resistance of the metal under test.

From pages 379 and 386, 1913, *Proceedings American Electric Railway Engineering Association.*

TABLE FOR DETERMINATION OF CURRENT FLOW ON PIPING FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS.

L = Distance between contacts in feet
E = Instrument reading in milli-volts,
K = Constant from table.

$$\frac{KE}{L} = \text{Current flow in amperes.}$$

TABLE 9

STANDARD CAST IRON PIPE.

(Based on a resistance of 0.00144 ohm per lb. ft.)

CLASSIFICATION					ACTUAL DIMENSIONS			
Nominal. Dia.in.	*Association Standard	Class Letter†	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	*K* = current for one milli-volt drop per ft. of continuous pipe. Amperes.
4	N	A	...	...	4.80	4.12	14.9	10.3
4	N	C	...	...	4.80	4.08	15.7	10.9
4	N	E	...	...	4.80	4.02	16.9	11.7
4	G	..	...	...	4.80	4.00	17.2	12.0
4	W	A	100	43	4.80	3.96	18.0	12.5
4	N	G	...	...	5.00	4.16	18.9	13.1
4	N	I	...	...	5.00	4.10	20.0	13.9
4	W	B	200	86	5.00	4.10	20.0	13.9
4	N	K	...	...	5.00	4.04	21.3	14.8

*W = American Water Works Association Standard.
N = New England Water Works Association Standard.
G = American Gas Institute Standard.
† = As used by the American Water Works Association and the New England Water Works Association.

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. *(Continued.)*

Classification					Actual Dimensions			
Nominal. Dia. in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	*K* = current for one milli-volt drop per ft. of continuous pipe. Amperes.
4	W	C	300	130	5.00	4.04	21.3	14.8
4	W	D	400	173	5.00	3.96	22.8	15.8
6	N	A	...	...	6.90	6.14	24.3	16.9
6	N	C	...	...	6.90	6.06	26.7	18.5
6	G	..	...	...	6.90	6.04	27.2	18.9
6	W	A	100	43	6.90	6.02	27.8	19.3
6	N	E	...	...	6.90	5.98	29.1	20.2
6	W	B	200	86	7.10	6.14	31.1	21.6
6	N	G	...	...	7.10	6.10	32.4	22.5
6	W	C	300	130	7.10	6.08	32.9	22.8
6	N	I	...	...	7.10	6.02	34.8	24.2
6	W	D	400	173	7.10	6.00	35.3	24.5
6	W	E	500	217	7.22	6.06	37.7	26.2
6	W	F	600	260	7.22	6.00	39.6	27.4
6	W	G	700	304	7.38	6.08	42.8	29.7
6	W	H	800	347	7.38	6.00	45.2	31.4
8	N	A	...	...	9.05	8.21	35.5	24.7
8	G	..	...	...	9.05	8.15	37.9	26.3
8	W	A	100	43	9.05	8.13	38.7	26.9
8	N	C	...	...	9.05	8.09	40.3	28.0
8	W	B	200	86	9.05	8.03	42.7	29.6
8	N	E	...	...	9.05	7.99	44.3	30.7
8	W	C	300	130	9.30	8.18	47.9	33.3
8	N	G	...	...	9.30	8.14	49.6	34.5
8	W	D	400	173	9.30	8.10	51.2	35.5
8	N	I	...	...	9.30	8.04	53.6	37.2
8	W	E	500	217	9.42	8.10	56.7	39.4
8	W	F	600	260	9.42	8.00	60.6	42.1
8	W	G	700	304	9.60	8.10	65.0	45.1
8	W	H	800	347	9.60	8.00	69.0	48.0
10	N	A	...	..	11.10	10.16	49.0	34.0
10	G	..	...	...	11.10	10.12	51.0	35.4
10	N	B	...	...	11.10	10.10	51.9	36.1

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. (*Continued*)

Classification					Actual Dimensions			
Nominal. Dia.in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	*K*-current for one milli-volt drop per ft. of continuous pipe. Amperes.
10	W	A	100	43	11.10	10.10	51.9	36.1
10	N	C	...	...	11.10	10.04	54.9	38.1
10	N	D	...	...	11.10	9.98	57.9	40.2
10	W	B	200	86	11.10	9.96	58.9	40.9
10	N	E	...	...	11.40	10.20	63.6	44.1
10	W	C	300	130	11.40	10.16	65.5	45.5
10	N	F	...	...	11.40	10.14	66.5	46.2
10	N	G	...	...	11.40	10.06	70.5	49.0
10	W	D	400	173	11.40	10.04	71.5	49.7
10	N	H	...	...	11.40	10.00	73.5	51.1
10	W	E	500	217	11.60	10.12	78.7	54.6
10	W	F	600	260	11.60	10.00	84.6	58.8
10	W	G	700	304	11.84	10.12	92.4	64.1
10	W	H	800	347	11.84	10.00	98.5	68.4
12	N	A	...	...	13.20	12.22	61.1	42.5
12	N	B	...	...	13.20	12.14	65.9	45.7
12	G	..	...	...	13.20	12.12	67.0	46.5
12	W	A	100	43	13.20	12.12	67.0	46.5
12	N	C	...	...	13.20	12.06	70.6	49.0
12	N	D	...	...	13.20	11.98	75.3	52.3
12	W	B	200	86	13.20	11.96	76.4	53.0
12	N	E	...	...	13.50	12.20	81.9	56.8
12	W	C	300	130	13.50	12.14	85.5	59.4
12	N	F	...	...	13.50	12.12	86.6	60.2
12	N	G	...	...	13.50	12.04	91.5	63.6
12	W	D	400	173	13.50	12.00	93.8	65.1
12	N	H	...	...	13.50	11.96	96.2	66.8
12	W	E	500	217	13.78	12.14	104.0	72.3
12	W	F	600	260	13.78	12.00	112.0	77.9
12	W	G	700	304	14.08	12.14	125.0	86.7
12	W	H	800	347	14.08	12.00	133.0	92.4
14	N	A	...	...	15.30	14.24	76.8	53.4
14	N	B	...	...	15.30	14.16	82.3	57.1
14	W	A	100	43	15.30	14.16	82.3	57.1

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. (*Continued.*)

Classification					Actual Dimensions			
Nominal. Dia. in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	K = current for one milli-volt drop per ft. of continuous pipe. Amperes.
14	N	C	...	...	15.30	14.08	87.9	61.0
14	N	D	...	...	15.30	13.98	94.8	65.8
14	W	B	200	86	15.30	13.98	94.8	65.8
14	N	E	...	...	15.65	14.25	103.0	71.4
14	W	C	300	130	15.65	14.17	108.0	75.0
14	N	F	...	...	15.65	14.15	109.0	76.2
14	N	G	...	...	15.65	14.07	115.0	80.0
14	W	D	400	173	15.65	14.01	119.0	82.8
14	N	H	...	...	15.65	13.99	121.0	83.9
14	W	E	500	217	15.98	14.18	133.0	92.4
14	W	F	600	260	15.98	14.00	145.0	101.0
14	W	G	700	304	16.32	14.18	160.0	111.0
14	W	H	800	347	16.32	14.00	172.0	120.0
16	N	A	...	...	17.40	16.30	90.9	63.1
16	N	B	...	...	17.40	16.20	98.9	68.6
16	W	A	100	43	17.40	16.20	98.9	68.6
16	G	..	...	...	17.40	16.16	102.0	70.7
16	N	C	...	...	17.40	16.10	107.0	74.1
16	N	D	...	...	17.40	16.00	115.0	79.6
16	W	B	200	86	17.40	16.00	115.0	79.6
16	N	E	...	...	17.80	16.30	125.0	87.1
16	N	F	...	...	17.80	16.20	133.0	92.6
16	W	C	300	130	17.80	16.20	133.0	92.6
16	N	G	...	...	17.80	16.10	141.0	98.2
16	W	D	400	173	17.80	16.02	147.0	102.3
16	N	H	...	...	17.80	16.00	149.0	103.5
16	W	E	500	217	18.16	16.20	165.0	114.5
16	W	F	600	260	18.16	16.00	181.0	125.5
16	W	G	700	304	18.54	16.18	201.0	139.5
16	W	H	800	347	18.54	16.00	215.0	149.0
18	N	A	...	...	19.25	18.11	104.0	72.5
18	N	B	...	...	19.25	17.99	115.0	79.8
18	W	A	100	43	19.50	18.22	118.0	82.2
18	N	C	...	...	19.50	18.12	127.0	88.5
18	N	D	...	...	19.50	18.00	138.0	95.8
18	W	B	200	86	19.50	18.00	138.0	95.8

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. (*Continued.*)

Classification					Actual Dimensions			K = current for one milli-volt drop per ft. of continuous pipe. Amperes.
Nominal. Dia. in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	
18	N	E	...	...	19.70	18.10	148.0	103.0
18	N	F	...	...	19.70	17.98	159.0	110.4
18	W	C	300	130	19.92	18.18	162.0	113.0
18	W	D	400	173	19.92	18.00	178.0	123.8
18	W	E	500	217	20.34	18.20	202.0	140.5
18	W	F	600	260	20.34	18.00	220.0	152.6
18	W	G	700	304	20.78	18.22	245.0	170.0
18	W	H	800	347	20.78	18.00	264.0	183.3
20	N	A	...	...	21.30	20.10	122.0	84.6
20	N	B	...	...	21.30	19.98	134.0	93.0
20	W	A	100	43	21.60	20.26	137.0	95.4
20	G	..	...	...	21.60	20.24	140.0	97.0
20	N	C	...	...	21.60	20.16	147.0	102.5
20	N	D	...	...	21.60	20.02	161.0	112.0
20	W	B	200	86	21.60	20.00	163.0	113.0
20	N	E	...	...	21.90	20.20	175.0	122.0
20	N	F	...	...	21.90	20.06	189.0	131.0
20	W	C	300	130	22.06	20.22	191.0	132.0
20	W	D	400	173	22.06	20.00	212.0	148.0
20	W	E	500	217	22.54	20.24	241.0	167.0
20	W	F	600	260	22.54	20.00	265.0	184.0
20	W	G	700	304	23.02	20.24	295.0	205.0
20	W	H	800	347	23.02	20.00	319.0	221.0
24	N	A	...	...	25.40	24.12	156.0	108.0
24	N	B	...	...	25.40	23.96	174.0	121.0
24	G	..	...	...	25.80	24.28	187.0	130.0
24	W	A	100	43	25.80	24.28	187.0	130.0
24	N	C	...	...	25.80	24.20	196.0	136.0
24	N	D	...	...	25.80	24.04	215.0	149.0
24	W	B	200	86	25.80	24.02	217.0	151.0
24	N	E	...	...	26.10	24.20	234.0	163.0
24	N	F	...	...	26.10	24.04	253.0	176.0
24	W	C	300	130	26.32	24.24	258.0	179.0
24	W	D	400	173	26.32	24.00	286.0	198.0
24	W	E	500	217	26.90	24.28	328.0	228.0
24	W	F	600	260	26.90	24.00	362.0	251.0

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. *(Continued.)*

Classification					Actual Dimensions			
Nominal. Dia.in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	*K* = current for one milli-volt drop per ft of continuous pipe. Amperes.
30	N	A	...	...	31.60	30.18	215.0	149.0
30	N	B	...	...	31.60	29.98	245.0	170.0
30	G	..	...	...	31.74	30.04	257.0	179.0
30	W	A	100	43	31.74	29.98	266.0	185.0
30	N	C	...	...	32.00	30.18	277.0	192.0
30	N	D	...	...	32.00	29.98	306.0	213.0
30	W	B	200	86	32.00	29.94	312.0	217.0
30	N	E	...	...	32.40	30.20	337.0	234.0
30	N	F	...	...	32.40	30.00	367.0	255.0
30	W	C	300	130	32.40	30.00	367.0	255.0
30	W	D	400	173	32.74	30.00	422.0	292.0
30	W	E	500	217	33.10	30.00	479.0	333.0
30	W	F	600	260	33.46	30.00	537.0	373.0
36	N	A	...	...	37.80	36.22	287.0	199.0
36	N	B	...	...	37.80	36.00	326.0	226.0
36	G	..	...	...	37.96	36.06	315.0	239.0
36	W	A	100	43	37.96	35.98	358.0	248.0
36	N	C	...	...	38.30	36.26	373.0	259.0
36	N	D	...	...	38.30	36.04	412.0	286.0
36	W	B	200	86	38.30	36.00	418.0	290.0
36	N	E	...	...	38.70	36.20	459.0	319.0
36	W	C	300	130	38.70	35.98	497.0	346.0
36	N	F	...	...	38.70	35.96	502.0	349.0
36	W	D	400	173	39.16	36.00	581.0	404.0
36	W	E	500	217	39.60	36.00	666.0	463.0
36	W	F	600	260	40.04	36.00	753.0	523.0
42	N	A	...	...	44.00	42.26	368.0	256.0
42	N	B	...	...	44.00	42.00	422.0	293.0
42	G	..	...	...	44.20	42.06	452.0	314.0
42	W	A	100	43	44.20	42.00	465.0	323.0
42	N	C	...	...	44.50	42.24	480.0	333.0
42	N	D	..	...	44.50	41.96	538.0	374.0
42	W	B	200	86	44.50	41.94	542.0	376.0
42	N	E	...	...	45.10	42.30	600.0	416.0
42	N	F	...	...	45.10	42.04	651.0	451.0

TABLE FOR DETERMINATION OF CURRENT FLOW ON STANDARD CAST IRON PIPE FROM MILLI-VOLT DROP ALONG CONTINUOUS LENGTH OF PIPE BETWEEN JOINTS. (*Continued.*)

Classification					Actual Dimensions			
Nominal dia. in.	*Association Standard	Class Letter †	Head Feet	Press. lbs. per sq. in.	Outs. dia. in.	Ins. dia. in.	Weight per ft. exclusive of hub-lb.	K = current for one milli-volt drop per ft. of continuous pipe. Amperes.
42	W	C	300	130	45.10	42.02	657.0	456.0
42	W	D	400	173	45.58	42.02	763.0	530.0
48	N	A	...	...	50.20	48.30	459.0	319.0
48	N	B	...	...	50.20	48.00	529.0	367.0
48	N	C	...	...	50.80	48.30	608.0	422.0
48	G	..	...	...	50.50	47.98	608.0	422.0
48	W	A	100	43	50.50	47.98	608.0	422.0
48	N	D	...	...	50.80	48.00	678.0	471.0
48	W	B	200	86	50.80	47.96	686.0	477.0
48	N	E	...	...	51.40	48.30	757.0	526.0
48	N	F	...	...	51.40	48.00	828.0	575.0
48	W	C	300	130	51.40	47.98	832.0	578.0
48	W	D	400	173	51.98	48.06	961.0	667.0
54	N	A	...	...	56.40	54.34	559.0	388.0
54	N	B	...	...	56.40	54.00	650.0	452.0
54	W	A	100	43	56.66	53.96	731.0	508.0
54	N	C	...	...	57.10	54.36	750.0	521.0
54	N	D	...	...	57.10	54.02	840.0	583.0
54	W	B	200	86	57.10	54.00	845.0	586.0
54	N	E	...	...	57.80	54.26	946.0	657.0
54	N	F	...	...	57.80	54.00	1041.0	723.0
54	W	C	300	130	57.80	54.00	1041.0	723.0
54	W	D	400	173	58.40	53.94	1230.0	854.0
60	N	A	...	...	62.60	60.40	664.0	460.0
60	N	B	...	...	62.60	60.00	782.0	543.0
60	W	A	100	43	62.80	60.02	836.0	581.0
60	N	C	...	...	63.40	60.40	910.0	632.0
60	W	B	200	86	63.40	60.06	1010.0	701.0
60	N	D	...	...	63.40	60.00	1028.0	714.0
60	N	E	...	...	64.20	60.40	1160.0	806.0
60	W	C	300	130	64.20	60.20	1220.0	848.0
60	N	F	...	...	64.20	60.00	1280.0	889.0
60	W	D	400	173	64.82	60.06	1455.0	1010.0
72	W	A	100	43	75.34	72.08	1178.0	819.0
72	W	B	200	86	76.00	72.10	1415.0	983.0
72	W	C	300	130	76.88	72.10	1745.0	1212.0
84	W	A	100	43	87.54	84.10	1445.0	1005.0
84	W	B	200	86	88.54	84.10	1878.0	1304.0

101. Resistance of Standard Steel or Wrought Iron Pipe.

TABLE 10

STANDARD STEEL (Or Wrought Iron) PIPE.

(Based on Resistance of steel 0.00021 ohms per lb. ft. Based on resistance of wrought iron 0.000181 ohm per lb. ft.)

Nominal dia. in.	Classification	Actual Dimensions		Weight per ft. plain ends-steel-lb.	*K* =current for one millivolt drop per ft. of continuous pipe-amperes.	
		Outside diameter inches	Inside diameter inches		Steel	Wrought iron
1/8	S	0.405	0.269	0.244	1.16	1.32
1/8	X	0.405	0.215	0.314	1.50	1.70
1/4	S	0.540	0.364	0.424	2.02	2.30
1/4	X	0.540	0.302	0.535	2.55	2.90
3/8	S	0.675	0.493	0.567	2.70	3.07
3/8	X	0.675	0.423	0.738	3.51	4.00
1/2	S	0.840	0.622	0.850	4.05	4.60
1/2	X	0.840	0.546	1.09	5.18	5.88
1/2	XX	0.840	0.252	1.71	8.16	9.28
3/4	S	1.050	0.824	1.13	5.38	6.11
3/4	X	1.050	0.742	1.47	7.03	7.98
3/4	XX	1.050	0.434	2.44	11.6	13.2
1	S	1.315	1.049	1.68	7.99	9.09
1	X	1.315	0.957	2.17	10.3	11.8
1	XX	1.315	0.599	3.66	17.4	19.8
1 1/4	S	1.660	1.380	2.27	10.8	12.3
1 1/4	X	1.660	1.278	3.00	14.3	16.2
1 1/4	XX	1.660	0.896	5.21	24.8	28.2
1 1/2	S	1.900	1.610	2.72	12.9	14.7
1 1/2	X	1.900	1.500	3.63	17.3	19.6
1 1/2	XX	1.900	1.100	6.41	30.5	34.7
2	S	2 375	2.067	3.65	17.4	19.8
2	X	2.375	1.939	5.02	23.9	27.2
2	XX	2.375	1.503	9.03	43.0	48.8
2 1/2	S	2.875	2.469	5.79	27.6	31.4
2 1/2	X	2.875	2.323	7.66	36.5	41.5
2 1/2	XX	2.875	1.771	13.69	65.2	74.2
3	S	3.500	3.068	7.57	36.0	41.0
3	X	3.500	2.900	10.2	48.8	55.6
3	XX	3.500	2.300	18.6	88.5	101.0
3 1/2	S	4.000	3.548	9.11	43.4	49.3
3 1/2	X	4.000	3.364	12.5	59.6	67.8
3 1/2	XX	4.000	2.728	22.8	109.0	124.0
4	S	4.500	4.026	10.8	51.4	58.4
4	X	4.500	3.826	15.0	71.3	81.1
4	XX	4.500	3.152	27.5	131.0	149.0

STANDARD STEEL (OR WROUGHT IRON) PIPE. *Continued.*

Nominal dia. in.	Classification	Actual Dimensions		Weight per ft. plain ends-steel-lb.	*K* = current for one millivolt drop per ft. of continuous pipe-amperes.	
		Outside diameter inches	Inside diameter inches		Steel	Wrought iron
4 1/2	S	5.000	4.506	12.5	59.8	67.9
4 1/2	X	5.000	4.290	17.6	83.9	95.3
4 1/2	XX	5.000	3.580	32.5	155.0	176.0
5	S	5.563	5.047	14.6	69.7	79.2
5	X	5.563	4.813	20.8	98.9	112.0
5	XX	5.563	4.063	38.5	183.0	209.0
6	S	6.625	6.065	19.0	90.3	103.0
6	X	6.625	5.761	28.6	136.0	155.0
6	XX	6.625	4.897	53.2	253.0	288.0
7	S	7.625	7.023	23.5	112.0	127.0
7	X	7.625	6.625	38.0	181.0	206.0
7	XX	7.625	5.875	63.1	300.0	342.0
8	S	8.625	8.071	24.7	118.0	134.0
8	S	8.625	7.981	28.5	136.0	155.0
8	X	8.625	7.625	43.4	206.0	235.0
8	XX	8.625	6.875	72.4	345.0	392.0
9	S	9.625	8.941	33.9	161.0	184.0
9	X	9.625	8.625	48.7	232.0	264.0
10	S	10.750	10.192	31.2	149.0	169.0
10	S	10.750	10.136	34.2	163.0	185.0
10	S	10.750	10.020	40.5	192.0	219.0
10	X	10.750	9.750	54.7	261.0	297.0
11	S	11.750	11.000	45.6	217.0	247.0
11	X	11.750	10.750	60.1	286.0	326.0
12	S	12.750	12.090	43.8	208.0	237.0
12	S	12.750	12.000	49.6	236.0	269.0
12	X	12.750	11.750	65.4	311.0	354.0
13	S	14.000	13.250	54.6	260.0	296.0
13	X	14.000	13.000	72.1	343.0	391.0
14	S	15.000	14.250	58.6	279.0	317.0
14	X	15.000	14.000	77.4	369.0	420.0
15	S	16.000	15.250	62.6	298.0	339.0
15	X	16.000	15.000	82.8	394.0	449.0

S = Standard pipe.
X = Extra strong pipe.
XX = Double extra strong pipe.

102. Resistance of Lead Cable Sheaths

TABLE 11.

TABLE FOR DETERMINING CURRENT ON LEAD CABLE SHEATHS FROM VOLTAGE DROP IN MEASURED LENGTH OF SHEATH.

Resistivity, 1 ft. length, 1 sq. in. sectional area = 0.00010 ohm

Outside diam. of lead sheath (in.)	Thickness of lead sheath (64th in.)	Resistance of lead sheath (ohm per ft.)	Current for 1 millivolt per ft. (amp.)	Outside diam. of lead sheath (in.)	Thickness of lead sheath (64th in.)	Resistance of lead sheath (ohm per ft.)	Current for 1 millivolt per ft. (amp.)
0.50	4	0.001163	0.860	2.00	6	0.0001781	5.61
0.50	5	0.000965	1.036	2.00	7	0.0001538	6.50
0.50	6	0.000836	1.196	2.00	8	0.0001359	7.36
0.625	4	0.000906	1.104	2 125	6	0.0001672	5.98
0.625	5	0.000745	1.343	2.125	7	0.0001443	6.93
0.625	6	0.000640	1.563	2.125	8	0.0001273	7.86
0.75	4	0.000741	1.350	2.25	6	0.0001575	6.35
0.75	5	0.000606	1.650	2.25	7	0.0001359	7.36
0.75	6	0.000518	1.931	2.25	8	0.0001198	8.35
0.875	4	0.000627	1.594	2.375	6	0.0001488	6.72
0.875	5	0.000511	1.957	2.375	7	0.0001284	7.79
0.875	6	0.000435	2.300	2.375	8	0.0001132	8.83
1.00	5	0.0004419	2.263	2.50	7	0.0001217	8.22
1.00	6	0.0003750	2.668	2.50	8	0.0001073	9.32
1.00	7	0.0003268	3.061	2.50	9	0.0000959	10.43
1.00	8	0.0002913	3.437				
				2.625	7	0.0001156	8.65
1.125	5	0.0003892	2.569	2.625	8	0.0001019	9.81
1.125	6	0.0003294	3.037	2.625	9	0.0000911	10.98
1.125	7	0.0002866	3.491				
1.125	8	0.0002547	3.926	2.75	7	0.0001102	9.08
				2.75	8	0.0000971	10.30
1.25	5	0.0003476	2.876	2.75	9	0.0000868	11.53
1.25	6	0.0002939	3.404				
1.25	7	0.0002552	3.918	2.875	7	0.0001050	9.51
1.25	8	0.0002265	4.415	2.875	8	0.0000927	10.79
				2.875	9	0.0000828	12.08
1.375	5	0.0003142	3.183				
1.375	6	0.0002650	3.773	3.00	8	0.0000887	11.28
1.375	7	0.0002299	4.35	3.00	9	0.0000792	12.62
1.375	8	0.0002038	4.91	3.00	10	0.0000716	13.96
1.50	6	0.0002416	4.14	3.125	8	0.0000849	11.77
1.50	7	0.0002092	4.78	3.125	9	0.0000758	13.18
1.50	8	0.0001853	5.40	3.125	10	0.0000686	14.58
1.625	6	0.0002218	4.51	3.25	8	0.0000815	12.27
1.625	7	0.0001920	5.21	3.25	9	0.0000728	13.74
1.625	8	0.0001698	5.89	3.25	10	0.0000659	15.19
1.75	6	0.0002051	4.88	3.375	8	0.0000783	12.77
1.75	7	0.0001772	5.64	3.375	9	0.0000700	14.29
1.75	8	0.0001567	6.38	3.375	10	0.0000633	15.83
1.875	6	0.0001906	5.25	3.50	8	0.0000755	13.24
1.875	7	0.0001648	6.07	3.50	9	0.0000674	14.84
1.875	8	0.0001456	6.87	3.50	10	0.0000609	16.42

103. Typical Report Sheets.

TIME	DATE ...... TESTED BY	POTENTIAL, CABLE TO												DIRECTION OF CURRENT ON CABLE	ELECTROLYSIS PITTINGS IN CABLES?	CABLES BONDED TOGETHER?	WATER IN MANHOLE?	DUCT MATERIAL?	CABLES PROTECTED?	CABLES SUPPORTED?
	LOCATION			DUCT		WATER		GAS		TRACK										
	AVE. OR ST.	+	−	+	−	+	−	+	−	+	−	+	−							
1150																				

CURRENT MEASUREMENTS

(This shows a condensed form in convenient size for a field notebook).

DATE AND TIME		Duration of Test Min.	Dist. betw. Cont. Feet	Amp. per Milli. K	Drop—Millivolts			Current—Amperes			DIRECTION.
					Max.	Min.	Ave.	Max.	Min.	Ave.	

POTENTIAL MEASUREMENTS

DATE AND TIME		Duration of Test Min.	Potential—Volts			Momentary bond Current Amp.
			Max.	Min.	Ave.	

FORM NO. 1

POTENTIAL SURVEY:—

CITY:— **DATE:—** **OBSERVER:—**

TIME	LOCATION	MEASUREMENTS		Duration of Test Min.	VOLTS POLARITIES REFER TO (A)			Max. Momentary Current Through Temporary Bond	REMARKS
		FROM (A)	TO (B)		Max.	Min.	Ave.		

FORM NO. 2

CURRENT SURVEY :—

CITY :— DATE :— OBSERVER :—

TIME	LOCATION	Size and Kind of Pipe	Dist. Bet. Contacts Feet	Duration of Test Min.	Direction of Current Flow	DROP IN MILLIVOLTS			CALCULATED CURRENT AMPERES			REMARKS
						Max.	Min.	Ave.	Max.	Min.	Ave.	

FORM NO. 3

DATA SHEET FOR ELECTROLYSIS SURVEY.

TESTS ON EXPOSED PIPE

City:— Date:— Time:— Observer:—
Location:—
Size and kind of pipe:—
Pavement:— Soil:—
Location of nearest trolley tracks:—
" " " " power station:—
Approximate age and condition of pipe:—

	Max.	Min.	Aver.
Duration of each test........minutes			
Potential, pipe to rails, volts	......	......	......
Current through temporary bond connection, amperes			......
Distance between contacts on pipe = ... feet			
Drop on pipe, millivolts	......	......	......
Current on pipe, amperes	......	......	......
Direction of current flow:—			

POTENTIAL TO OTHER PIPES, ETC.:—

SIMULTANEOUS DROP MEASUREMENTS FOR RESISTANCE OF JOINTS.

		EQUIVALENT RESISTANCE	
		Feet of pipe.	Ohms.
Drop in...... feet of pipe =	millivolts		
Drop across first joints	"	....	....
" " second joint =	"	....	....

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1916

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its Thirty-Second Annual Report, for the fiscal year ending April 30, 1916. A General Balance Sheet showing the financial condition of the Institute on April 30, 1916, together with other financial statements, is included herein.

The Board has endeavored, as far as possible, to keep the membership informed of its proceedings by publishing monthly in the Institute PROCEEDINGS a resumé of the business transacted at each meeting. These notices, however, are necessarily incomplete, as many important matters are considered which cannot be disposed of at one meeting and which must be held over for future consideration and action. Eventually such matters are dealt with in subsequent issues.

Directors' Meetings.—During the year the Board of Directors held 10 regular meetings, one adjourned meeting, and one special meeting. The adjourned meeting was held on December 11, 1915, for the purpose of considering the report of the Constitutional Revision Committee. The special meeting was held on January 21, 1916, for the purpose of acting upon an invitation from President Wilson to President Carty to nominate from the Institute's membership, candidates for appointment by the Secretary of the Navy upon the Organization for Industrial Preparedness, referred to elsewhere in this report.

Eleven of these meetings were held in New York, and one in Deer Park, Md., during the Annual Convention.

Annual Convention.—The Thirty-Second Annual Convention was held in Deer Park, Maryland, June 29-July 2, 1915. The total attendance was 202, which included 43 ladies. Although the attendance was small, due possibly to the location being somewhat remote from the larger membership centers, the convention was very successful from a technical and social standpoint. Thirty-one papers were presented at the seven technical sessions.

Panama-Pacific Convention.—The Panama-Pacific Convention was held in San Francisco September 16-18, 1915. It was arranged chiefly to provide an Institute meeting in San Francisco for Pacific coast members during the Panama-Pacific Exposition in place of the International Electrical Congress, which had been scheduled to be held on the same dates, but which had been postponed. The convention was unusually successful. Three hundred and fifty-five members registered, of which a considerable number were eastern members visiting the Exposition and attending the International Engineering Congress. Twenty-six papers were presented on a variety of engineering subjects.

Midwinter Convention, New York.—The Fourth Midwinter Convention was held in New York on February 8 and 9, 1916. The total registered attendance was 671, of which number 380 were members. The 291 guests included 175 ladies. Eleven papers were presented and four technical sessions were held. A subscription dinner-dance was held at the Hotel Astor on the evening of February 8, which was attended by 425 members and guests. The proceeds from the sale of tickets to this function covered all of the expenses and provided a surplus which will be available towards defraying the expenses of future midwinter social functions.

Philadelphia Meeting.—An Institute meeting was held in Philadelphia, Pa., on October 11, 1915, under the auspices of the Philadelphia Section. Three papers were presented and the total attendance was 200. This is the third annual meeting of this kind to be held in Philadelphia at the opening of the active season.

St. Louis Meeting.—On October 19 and 20, 1915, Institute members in the middle west were given an opportunity to attend a two-day Institute meeting which was held in St. Louis, Mo., under the auspices of the St. Louis Section, on the occasion of the 100th meeting of that Section. Eleven papers were presented, and the total attendance was 201. Members of the Associated Engineering Societies of St. Louis, with which the Section is affiliated, participated in this meeting.

Water Power Meeting, Washington, D. C.—This meeting was held in Washington on April 26, 1916, under the auspices of the Washington Section and the Committee on Development of Water Power. Five very carefully prepared papers were presented on the general subject of the relation of water power to the industrial advancement of the country. Two-hundred and fifty members and invited guests attended the meeting.

National Meeting, May 16, 1916.—An event unique in the history of the Institute and one which is attracting widespread interest will take place on May 16, 1916. This is a National Meeting which will be held simultaneously through the medium of the long distance telephone in six different cities; namely, San Francisco, Chicago, Atlanta, Philadelphia, New York and Boston. The purpose of the meeting is to commemorate the achievements of Institute members in the fields of communication, transportation, lighting and power. Incidentally it is being held on the date of the Annual Meeting of the Institute, and although the business coming before the Annual Meeting will be transacted in the afternoon at the business meeting, it is planned to reserve a part of it for the National Meeting in the evening.

Other Meetings.—In addition to these special meetings, held in various parts of the country for the benefit of the membership at large, eight regular monthly meetings were held in New York, with an average attendance of 300.

The Sections and Branches have also continued active and have held a large number of regular monthly meetings as shown by the tabulated statement in the report of the Sections Committee.

President.—President Carty has presided at all meetings of the Institute held during the year, with the exception of the meeting in St. Louis, and also at all meetings of the Board of Directors. During the year he has attended the following meetings: Detroit, September 9, 1915, Joint Session of A. I. E. E. at Convention of Association of Iron and Steel Electrical Engineers: Panama-Pacific Convention, San Francisco, September 16-18, 1915; Institute Meeting, Philadelphia, October 11, 1915; Schenectady Section, October 12, 1915; Boston Section, October 13, 1915; Pittsburgh Section, December 4, 1915; Ithaca Section, March 25, 1916; Water Power Meeting, Washington, April 26, 1916.

International Engineering Congress.—The International Engineering Congress has already received such wide publicity through its Committee of Management that no extended reference to it is necessary in this report. The Institute was one of the five national engineering societies which planned the Congress and which was interested in its success. It was held in San Francisco on the dates scheduled, September 20-25, 1915, and was eminently successful in every way.

The total registered attendance at the Congress was 851, of which number 71 were from 20 foreign countries. Fifty-two technical sessions were held, and over 200 papers were presented on a wide range of engineering subjects. In addition to the registered attendance over 600 cards of admission were issued so that the attendance at the various sessions was well over 1,500. The Committee of Management is still acting, principally with the publication and distribution of the volumes of the transactions, which it is estimated will be in the neighborhood of 10,000 to 12,000. A full report will be submitted by the committee to the participating societies in the near future.

National Preparedness.—The Institute has taken an active part in a number of the movements which have been organized recently in the interest of adequate national preparedness. Chief among these are the National Engineer Reserve, the Naval Consulting Board, and the Organization for Industrial Preparedness.

National Engineer Reserve.—The suggestion for the organization of a National Engineer Reserve was first made early in 1915, and shortly thereafter a joint committee was formed of representatives of the American Society of Civil Engineers, the American Society of Mechanical Engineers, the American Institute of Mining Engineers, the American Institute of Electrical Engineers, and the American Institute of Consulting Engineers, to cooperate with the war department in the organization of such a reserve. The members of this committee being widely separated geographically, making full attendance at meetings difficult and impracticable a smaller working committee was formed consisting of the five chairman of the individual committees of each society constituting the joint committee. This arrangement greatly facilitated the work. The committee has held conferences with Major General Leonard Wood, officers of the General Staff of the U. S. Army and of the War College, and with the chairmen of the House and Senate legislative committees on military affairs. The result of this work is that several of the military measures before Congress embody provisions for an Officers Reserve Corps under which the engineers of the country may take service. The committee is now waiting for the Navy Department to formulate its plan for an increase of the naval forces, and as soon as a decision has been reached by that Department, the committee will take up the question of an engineer reserve for the Navy similar to that contemplated for the Army.

U. S. Naval Consulting Board.—On July 19, 1915, the Institute was invited by the Hon. Josephus Daniels, Secretary of the U. S. Navy Department, to select two members for appointment by Secretary Daniels upon a proposed advisory committee to be presided over by Mr. Thomas A. Edison and to be composed of men recognized throughout the country for their inventive genius and engineering achievements, to assist the Navy Department, both instructively and critically, in the development of such new ideas for naval advance as might be presented and found worthy of consideration. The underlying idea was to make available the latent inventive and engineering genius of our country to improve the navy, and to bring the officers of the service into more intimate contact with the industrial resources of the country. Similar invitations were extended to ten other scientific and engineering organizations. The two members officially selected for this service by the Institute were Mr. Frank Julian Sprague, of New York, and Mr. Benjamin G. Lamme, of Pittsburgh, Pa., both of whom were appointed by Secretary Daniels as members of the Naval Consulting Board. The excellent work of the Board has already received so much attention from the public press that no further statement regarding it is necessary in this report. Recently its usefulness has been greatly enlarged by the organization of representatives from each state in the Union to assist in the work of collecting data regarding the manufacturing resources of the country.

Organization for Industrial Preparedness.—This movement was inaugurated as the result of the valuable service rendered by the Naval Consulting Board. Its purpose, as expressed in President Wilson's letter to President Carty inviting the Institute to nominate representatives, is to assist the Naval Consulting Board in the work of collecting data for use in organizing the manufacturing resources of the country for the public service in time of emergency. The Institute was invited to nominate, for the approval of the Secretary of the Navy, a representative from its membership from each state in the Union to act in conjunction with representatives of the American Society of Civil Engineers, the American Society of Mechanical Engineers, the American Institute of Mining Engineers and the American Chemical Society. At the call of President Carty the Board of Directors of the Institute held a special meeting on January 21, 1916, to act upon this invitation, and at this meeting President Carty was empowered to select the nominees on behalf of the Institute. A list of these nominees was subsequently submitted to the Secretary of the Navy and the appointments were made. The state representatives are officially known as the *State Directors of the Organization for Industrial Preparedness, and Associate Members of the Naval Consulting Board of the United States*, and it will be the duty of these directors to make a canvass of the industrial establishments in their respective States and have them fill out a confidential form giving in detail data regarding their manufacturing and producing resources. On April 20, 1916, President Carty issued a letter to all Institute members in the United States appealing to them to assist in the work.

Representatives.—In addition to its regular representation upon the various joint committees and other local and national bodies with which it has been affiliated in past years, the Institute has also appointed special representatives on numerous occasions during the year in connection with matters of interest to the Institute and to the engineering profession, especially in civic affairs and matters pertaining to legislation affecting the profession.

Committees.—There has been no change in the number and character of the standing, technical and special committees, but a committee has been investigating the fields of the respective technical committees, and it is probable that there will be some additions next year. With one or two exceptions all of the committees have been more or less active. Abstracts of the reports of the chairmen of many of the Institute committees to the Board of Directors are included herein as follows:

Sections Committee.—The Sections Committee is able to report a gratifying increase in activity and interest on the part of the Sections and Branches during the year.

Although the number of meetings has not greatly increased, the attendance has been considerably larger, notwithstanding the fact that two Sections have necessarily been inactive during the present year; namely, Mexico and Toronto. The Toronto Section is inactive only temporarily.

Two new Sections were organized during the year: one at Denver, Colo., on May 18, 1915, and the other at Kansas City, Mo., on April 14, 1916. The Denver Section has made an excellent start and is doing good work. The Kansas City section was just organized a month ago and has therefore not yet had an opportunity to become active. The officers, however, are enthusiastic and the Section will doubtless be of great usefulness to the membership.

New Branches were organized at the Carnegie Institute of Technology, Clarkson College of Technology, and the Brooklyn Polytechnic Institute.

On April 14, 1916, the Board of Directors, acting upon the recommendation of the Sections Committee authorized a conference of Branch delegates at the Annual Convention, similar to the conference of Section delgates which of late years has become such a prominent feature of the annual conventions. It was considered inexpedient, however, to recommend that the transportation expenses of the Branch delegates be paid from the Institute treasury.

In accordance with Section 60 A of the Institute by-laws, which was adopted upon recommendation of the committee, the Chairman is receiving suggestions of questions for discussion at the coming conference of Section delegates at the Cleveland Convention.

A tabulated table showing the activity of the Sections and Branches during the past five years follows:

	For Fiscal Year Ending				
	May 1 1912	May 1 1913	May 1 1914	May 1 1915	May 1 1916
Sections					
Number of Sections	28	29	30	31	32
Number of Section meetings held	231	244	233	246	251
Total Attendance	19,800	22,825	22,626	23,507	28,553
Branches					
Number of Branches	42	47	47	52	54
Number of Branch meetings held	281	357	306	328	360
Attendance	10,255	11,808	11,617	12,712	15,166

Meetings and Papers Committee.—The Meetings and Papers Committee has held regular monthly meetings throughout its term of office, at which meetings the disposition of all manuscripts submitted has been attended to and the regular Institute meetings and conventions decided upon. In addition to the monthly meetings in New York, meetings have been arranged for by this committee in St. Louis, Philadelphia and Washington. The Panama-Pacific Convention, the Midwinter Convention, the Annual Convention, Cleveland, and the Pacific Coast Convention at Seattle, have also been arranged for by this committee. Following its practise in previous years all manuscripts which have been submitted have first been passed upon by one of the special technical committees before being finally acted upon by the main committee.

Standards Committee.—The 1915 edition of the Standardization Rules, representing the work of the Standards Committee of 1914-1915, was presented to and approved by the Board of Directors at the Deer Park Convention meeting, July 1, 1915. The revision was not radical, but rather a completion and clarification of the radical revision of December 1, 1914.

The present committee has held monthly meetings for the consideration of amendments and additions. The work has been largely carried on through the medium of 20 sub-committees charged with various parts of the field, whose reports have been reviewed by the whole committee. No final action will be taken on the proposed amendments until the May meeting, which will probably last for several days.

The changes to be considered at the May meeting are for the most part not radical, although they constitute distinct improvements. These will be presented to the Board of Directors at the Cleveland Convention in June, and if approved will be incorporated in the 1916 edition which will become effective on August 1.

In order to insure greater continuity of policy and method in the work of the Standards Committee from year to year the committee will present to the Board of Directors for its approval a set of by-laws with the recommendation that any future changes thereto can be made only with the sanction of the Board.

During the year a number of additions have been made to the list of cooperating societies, which includes several foreign societies.

Code Committee.—The Code Committee has continued to represent the Institute on the Electrical Committee of the National Fire Protection Association. Only one meeting was held, in Boston, and nothing transpired at this meeting of sufficient importance to merit special mention.

A sub-committee of the Code Committee spent much time cooperating with the U. S. Bureau of Standards during the year, working on the National Safety Code which the Bureau is formulating and which it expects to issue sometime in the near future. This was a continuation of the kind of work carried on last year, and represents the real activity of the Code Committee for the year.

Library Committee.—The united libraries of the founder societies and the United Engineering Society are now controlled and administered as one joint library by the Library Board of the United Engineering Society under an agreement which took effect on January 1, 1915, and in accordance with the by-laws of that society. The first annual report of the Library Board, for the year 1915, was issued and published in pamphlet form in January 1916. A synopsis of the report appeared in the Institute PROCEEDINGS for February 1916. It includes many interesting statistics of the accessions to the library, its utilization, its finances, and a list of the donors of books and pamphlets.

Railway Committee.—The Railway Committee this year has cooperated with the Standards Committee in respect to the revision of Rule No. 418 of the Standardization Rules, and has made suggestions regarding the rule for incorporation in the final edition of the Rules. Some consideration has been given to a more standard terminology for electric railway devices and the standardization of voltages for railroad purposes.

Transmission Committee.—The Transmission Committee has this year continued its practise of securing a consensus of opinion of the best informed engineers and operating men on some selected subject or subjects and either reproducing or digesting the material for the benefit of the membership. This year the committee will make reports at the Annual Convention on experiences in the effect of altitude in the operating temperature of electrical apparatus, and in the use of the grounded neutral in high tension systems.

Electric Lighting Committee.—The Electric Lighting Committee has held several meetings during the year at which the principal subject of discussion was the arrangement of circuits for street lighting purposes. A paper on this subject will be presented at the Annual Convention.

Industrial Power Committee.—As in previous years, the Industrial Power Committee cooperated with the Sections and Branches in arranging meetings on the subject of industrial power. The Cleveland Section appointed a local industrial power committee and later a considerable number of Sections and Branches followed its example. Each Section and Branch was requested to hold at least one meeting during the year on the subject of industrial power, and the local committees were of great assistance in arranging for these meetings. The Industrial Power Committee was also able to obtain for the use of the Sections and Branches a number of lantern slide lectures. The committee has been assigned one session of the Annual Convention. Four meetings were held during the year.

Electrochemical Committee.—The Electrochemical Committee has confined its work to efforts to obtain suitable papers on electrochemical subjects which the committee considered might be of general interest to the membership. The committee arranged for the joint meeting with the New York Section of the American Electrochemical Society held in New York on March 10, 1916.

Electrophysics Committee.—The work of the Electrophysics Committee has been directed chiefly to obtaining and reviewing, for the Meetings and Papers Committee, papers on subjects relating to the physical theory underlying the application of electricity to electrical engineering. Six papers have thus far been obtained and two others promised. Of the six, three have already been presented, one will be presented at the Annual Convention, and two will be offered for future meetings.

Iron and Steel Industry Committee.—This committee has arranged for a joint session between the A.I.E.E. and the Association of Iron and Steel Electrical Engineers, for Wednesday, September 20, 1916, during the annual convention of the Association to be held in Chicago, September 18-22, 1916.

Committee on Use of Electricity in Mines.—A session of the Panama-Pacific Convention held in San Francisco in September 1915 was devoted to mining work and a number of papers were presented dealing particularly with metal mine problems. Some work was also done by the committee in conjunction with the U. S. Bureau of Mines regarding rules for electrical installation in mines, but owing to business conditions it has not been possible to get the members of the committee together for a thorough discussion of the subject.

Committee on Use of Electricity in Marine Work.—The work of this committee has been directed, first, to obtaining papers dealing with electrical installations on shipboard, and, second, to continuing the work carried on during the previous two years in securing standard rules for various types of marine installations. A paper on this subject was presented at the Panama-Pacific Convention, and several papers are in view dealing with auxiliary power plants on shipboard for lighting, and for power for radio telegraph sets in cases of emergencies.

A sub-committee of this committee is now at work in conjunction with Lloyds and the American Bureau of Shipping in an endeavor to bring up to date and standardize the rules of the various building and insurance societies.

Protective Apparatus Committee.—The work of the Protective Apparatus Committee during the year might be divided into five categories, as follows: 1. An endeavor to standardize lightning arresters and similar protective devices. 2. Consideration and discussion of the factors involved in attempting to standardize the rating of oil switches. 3. An analysis of the protective problems connected with relays, split conductor cables, and like protective means. 4. Collection of data on partially solved problems relating to protective devices and continuity of service in the transmission of electrical energy. 5. Presentation of data in the form of papers; four dealing with operating experiences with protective devices, three on pressing problems relating to line insulators, and one on the theory of parallel grounded wires.

Committee on Records and Appraisals of Properties.—The geographical distribution of the committee has made it necessary to carry on its work through the medium of correspondence. One of the results of the committee's work was the presentation of several very important papers on various phases of appraisal work at the Panama-Pacific Convention.

A considerable number of conferences have been held by members of the committee, as a result of which it is planned to present at the October meeting in New York a number of papers on appraisal work and a topical discussion on methods of keeping inventories and appraisals up to date.

In view of the wide variety of opinions concerning inventory and appraisal work, the committee believes that it is not wise to attempt to present anything in the nature of a complete report but recommends the continuance of the committee in order that further study and investigation may be made of this important subject.

Educational Committee.—The Educational Committee has decided to begin the preparation of a list of topics suitable for advanced study, research and invention in electrical engineering. This was considered to be a piece of work which might be of benefit to colleges of engineering, and at the same time of such a technical nature as to be outside of the scope of activity of various educational associations. It is felt that work of this kind might well be made a part of the regular duties of the Educational Committee or one of its sub-committees. The committee would thus in time establish closer relations with colleges of engineering, research laboratories and individual investigators, and would become a center of information and a source of wholesome inspiration for electrical research in this country. A list of topics for research with some suggestions, compiled by the chairman of the committee, has been accepted for presentation at the Annual Convention.

Editing Committee.—The Editing Committee has had general supervision over the discussions in the PROCEEDINGS and the contents of the TRANSACTIONS published during its incumbency. The method of handling this material has been the same as in the previous two or three years and it appears to have met with general satisfaction. The only important typographical changes which have been adopted for the current year have been the new style for the cover and the combination of the Section I and Section II tables of contents on the first page of the PROCEEDINGS immediately inside the cover.

Committee on Development of Water Power.—During the past year this committee, through its members, has endeavored to keep informed respecting the progress of legislation affecting water power development and other allied questions. The committee has held several meetings, a large number of informal conferences, and has exchanged much correspondence.

In the fall of 1915 the committee accepted an invitation from Governor James Withycombe of the State of Oregon to send a delegate to address a Western Water Power Conference held at Portland, Oregon, September 21, 22 and 23. Mr. John H. Finney, a member of the committee, was appointed and presented to the conference a brief which had been prepared by the committee.

Acting jointly with the Meetings and Papers Committee, this committee arranged for the special Institute meeting held in Washington, D. C., under the auspices of the Washington Section, on April 26, at which various aspects of the water power situation were treated through the medium of a carefully prepared program.

Public Policy Committee—The Public Policy Committee has held four meetings during the year, at which various matters referred to the committee were considered and discussed. Among the more important questions reported upon by the committee to the Board of Directors were the following: Legislation providing for federal support for engineering experiment stations in each state; water power legislation; engineering cooperation; translation of standardization rules into foreign languages; legislation affecting the engineering profession.

Committee on Relations of Consulting Engineers.—On May 13, 1915, the committee submitted to the Board of Directors a proposed schedule of fees as a general guide for consulting engineers. No other matters have developed requiring the attention of the committee.

U. S. National Committee of the International Electrotechnical Commission—The War has naturally interfered with the international activities of the Commission, but nevertheless a considerable amount of work has been carried on among the individual national committees.

In America, electrical engineering standardization has been confined to the work of the A. I. E. E. Standards Committee. The British Standardization Rules for Electrical Machinery have been published during the year, and are believed to be in substantial conformity with the last edition (1915) of the A. I. E. E. Standardization Rules, as well as with the international rules thus far adopted by the I. E. C.

The Annual Report of the Honorary Secretary of the Commission, dated January 1916, which has been received from the Central Office, indicates that the work of the Commission, in abeyance for the present, should be expected to recontinue as soon as the peace of the world shall have been restored.

The U. S. National Committee held one meeting, in New York, in November 1915.

Constitutional Revision Committee.—The Constitutional Revision Committee was appointed at the beginning of the administrative year, and immediately began work upon the revision of the constitution. All suggestions which had been received since the last amendment to the constitution in 1912 were considered by the committee. Requests for further suggestions were made to each member of the present Board of Directors, each past-president, and each Section chairman. As the result of the suggestions received and those made by the members of the committee the proposed amendments were agreed upon and submitted to the Board of Directors in December 1915. The amendments are now being voted upon by the membership and the result of the vote will be made known at the Annual Meeting.

Employment Department.—The usefulness of the Employment Department has increased greatly during the year. A considerable number of Institute members have been helped to positions, and employers are more and more taking advantage of the facilities offered by the Institute for placing them in touch with desirable technical men. The Institute continues to publish without charge in the monthly PROCEEDINGS announcements of vacancies and men available.

Board of Examiners.—The Board of Examiners has held 11 meetings during the year. It has considered and referred to the Board of Directors with its recommendations a total of 1,419 applications of all kinds. In addition to these, the Board has reviewed 29 applications for a second and third time. Although the total number of applications is less than last year, the amount of time devoted to the work by the Board was considerably greater this year. The reason for this is that there were less applications for admission as Associates, which require very little detailed examination, but more applications for the higher grades, to which much time must necessarily be devoted. In considering applications for admission and transfer to the grade of Fellow the Board has adhered rigidly to its interpretation of the constitutional requirements, as may be inferred from the following figures showing that only 10 applicants were recommended for this grade, and 20 were not recommended.

Applications for Admission.

Recommended for grade of Associate	624	
Not recommended for grade of Associate	1	625
Recommended for grade of Member	44	
Not recommended for the grade of Member	14	58
Recommended for grade of Fellow	3	
Not recommended for Fellow	5	8
Recommended for enrolment as students	643	643

Applications for Transfer.

Recommended for grade of Member	54	
Not recommended for grade of Member	9	63
Recommended for grade of Fellow	7	
Not recommended for grade of Fellow	15	22
Total number of applications considered		1419
Applications reconsidered		29
Admission and transfer all grades		1448

Membership Committee.—The work of the Membership Committee began early last fall when plans were formulated assigning a definite portion of the work to each member of the committee. This, based upon well established precedent, aimed to increase the membership without the employment of undignified methods. Later it was decided to extend operations in the same and new fields.

The work of the committee, into which the individual members entered with considerable interest and activity, resulted in the filing of 777 applications for membership, and the laying of a foundation for the work of the succeeding committee.

The Membership Committee, believing its duty to be the retention of existing as well as the acquisition of new members, has during the year cooperated with the Secretary of the Institute in securing the payment of dues in arrears, and, in general, seeking and endeavoring to remove the cause of difficulty. So much has been accomplished that it is urgently recommended that this function be delegated to the Membership Committee each year.

The following tabulated statement shows the number of members in each grade, the total membership, and the additions and deductions that have been made during the year:

	Honorary Member	Fellow	Member	Associate	Total
Membership, April 30, 1915.	5	448	1079	6522	8054
Additions:					
Elected..................	....	4	41	584	....
Transferred..............	....	6	47	....	....
Reinstated...............	....	....	7	46	....
Deductions:					
Died.....................	....	2	7	27	....
Resigned.................	....	....	13	206	....
Dropped..................	....	2	13	254	....
Transferred..............	....	....	4	49	....
Membership, April 30, 1916..	5	454	1137	6616	8212

Net increase in membership during the year.. 158

Deaths.—The following deaths have occurred during the year:

Fellows.—Henry A. Mavor, Louis Duncan.

Members.—Fred S. Pearson, Max Hebgen, C. E. Hogle, R. A. McKee, James I. Ayer, W. W. Cole, W. C. Robinson.

Associates.—J. A. Culverwell, I. W. Moore, O. C. F. Hague, J. F. McElroy, E. J. Correa, R. W. Farr, Eugene Fischer, W. J. Henry, Geo. F. Kenyon, Joseph Herzog, John W. Barnett, R. C. Watson, Wm. F. Endress, Roy N. Wooster, Crellin Cartwright, W. C. Andrews, James S. Anthony, W. G. Roome, Frank Zencak, W. E. Dickinson, F. H. Varney, E. F. Cannon, J. Ray Wilson, C. J. H. Woodbury, John C. Manley, Chas. F. Baldwin, George H. Stockbridge. Total deaths, 36.

Finance Committee.—The following correspondence and financial statements form a complete summary of the work of the Finance Committee for the year.

Board of Directors, New York, May 12, 1916
American Institute of Electrical Engineers.
Gentlemen:

Your Finance Committee respectfully submits the following report for the year ending April 30, 1916.

During the past year the committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes and otherwise performed the duties prescribed for it in the Constitution and By-Laws. Haskins & Sells, certified public accountants, have audited the books, and their certification of the Institute finances follows.

In company with your Treasurer, Secretary, and a member of the firm of accountants, the committee has examined the securities held by the Institute and finds them to be as stated in the accountants' report.

In accordance with the recommendation of your committee in their report dated May 11, 1915, the Board of Directors instructed the Finance Committee to liquidate the mortgage upon the lands on which the Engineering Societies Building stands. This mortgage, amounting to $54,000.00, was paid June 25, 1915, and therefore the Institute is now free from all indebtedness save for current liabilities as shown in the accompanying report.

Respectfully submitted.
(Signed) J. Franklin Stevens,
Chairman, Finance Committee.

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS
30 BROAD STREET
NEW YORK

CABLE ADDRESS "HASKSELLS"

WATERTOWN
BALTIMORE
PITTSBURGH
CLEVELAND
CHICAGO
ST. LOUIS
ATLANTA
DENVER
SAN FRANCISCO
LONDON, E. C.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

CERTIFICATE

We have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1916, and

WE HEREBY CERTIFY that the accompanying General Balance Sheet properly sets forth the financial condition of the Institute on April 30, 1916, that the Statement of Income and Profit & Loss for the year ended that date is correct, and that the books of the Institute are in agreement therewith.

HASKINS & SELLS
Certified Public Accountants.

NEW YORK.
May 12, 1916.

AMERICAN INSTITUTE OF

GENERAL BALANCE SHEET

EXHIBIT A.

ASSETS.

LAND AND BUILDING:			
Interest in United Engineering Society's Real Estate No. 25 to 33 West 39th Street:			
Building		$353,346.61	
Land (One-third of Cost)		180,000.00	
Total Land and Building			$533,346.61
EQUIPMENT:			
Library—Volumes and Fixtures		$ 39,217.30	
Works of Art, Paintings, etc		3,001.35	
Office Furniture and Fixtures		11,229.48	
Total		$ 53,448.13	
Less Reserve for Depreciation		6,989.01	
Remainder—Equipment			$ 46,459.12
INVESTMENTS:			
BONDS—City of Wilmington, Delaware, 4½%, 1934, Par $15,000			$ 15,938.83
WORKING ASSETS:			
Publications entitled "Transactions," etc		$ 10,908.50	
Badges		602.95	
Total Working Assets			$ 11,511.45
CURRENT ASSETS:			
Cash		$ 6,740.09	
Accounts Receivable:			
Members, for Entrance Fees and Past Dues		7,750.00	
Advertisers		446.70	
Miscellaneous		580.94	
Interest Accrued—Investments		56.25	
Interest Accrued—Bank Balances		107.73	
Total Current Assets			$ 15,681.71
FUNDS:			
Life Membership Fund:			
Cash	$ 349.89		
Chicago, Burlington & Quincy Railroad Company, 4%, 1958, Par $5,000.00	4,868.75		
Interest Accrued	33.33	$ 5,251.97	
International Electrical Congress of St. Louis—Library Fund:			
Cash	$ 756.39		
New York City Bonds, 4½%, 1957, Par $2,000.00	2,261.47		
Interest Accrued	45.00	3,062.86	
MAILLOUX FUND:			
Cash	$ 104.10		
New York Telephone Company Bond, 4½%, 1939	1,000.00		
Interest Accrued	22.50	1,126.60	
Midwinter Convention Fund—Cash		158.93	
Total Funds			9,600.36
Total			$632,538.08

ELECTRICAL ENGINEERS

April 30, 1916

Liabilities

Current Liabilities:		
Accounts Payable—Subject to Approval by the Finance Committee	$ 7,146.64	
Dues Received in Advance	1,322.97	
Entrance Fees and Dues Advanced by Applicants for Membership	455.50	
Total Current Liabilities		$ 8,925.11
Fund Reserves:		
Life Membership Fund	$ 5,251.97	
International Electrical Congress of St. Louis—Library Fund	3,062.86	
Mailloux Fund	1,126.60	
Midwinter Convention Fund	158.93	
Total Fund Reserves		9,600.36
Surplus: Per Exhibit " B "		614,012.61
Total		$63.2538.08

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

STATEMENT OF INCOME AND PROFIT AND LOSS

FOR THE YEAR ENDED APRIL 30, 1916

EXHIBIT B.

REVENUE:			
Entrance Fees		$ 3,565.00	
Dues		87,695.28	
Student's Dues		4,621.50	
Transfer Fees		520.00	
Advertising		8,049.43	
Subscriptions		2,688.38	
Sales of " Transactions," etc.		2,323.86	
Badges Sold	$1,684.00		
Less Cost	1,475.05		
		208.95	
Interest on Investments		965.97	
Interest on Bank Balances		533.92	
Exchange		27.53	
Total			$111,199.82
EXPENSES:			
Meetings and Papers Committee:			
Salaries		$ 5,425.00	
Binding and Mailing Proceedings		6,426.13	
Printing Proceedings		11,121.75	
Engraving Proceedings		2,349.12	
Paper and Cover Paper		6,320.34	
Envelopes		786.83	
Stationery and Miscellaneous Printing		89.95	
General Expenses		128.23	
Meetings		5,983.43	
Volume No. 32		5.90	
Volume No. 33		12,422.92	
Volume No. 34		1,476.64	
Total		$ 52,536.24	
Deduct Increase in Inventory of Publications:..			
May 1, 1915	$ 9,650.75		
April 30, 1916	10,908.50	1,257.75	$ 51,278.49
Executive Department:			
Salaries		$ 16,448.50	
General Expenses		1,980.06	
United Engineering Society—Assessments		4,800.00	
Express		412.59	
Postage		2,710.56	
Advertising		2,035.76	
Stationery and Miscellaneous Printing		3,111.67	
Year Book and Catalogue		3,750.85	
Interest on Bond and Mortgage		360.00	34,609.99
FORWARD		$	$ 85,888.48
REVENUE—(Forward)			$111,199.82

Revenue—(Forward)		$111,199.82
Expenses—(Forward)		$ 85,888.48
Sections Committee:		
Section Meetings	$ 5,338.94	
Branch Meetings	162.33	
Delegates' Convention Expenses	1,574.05	
Salaries, New York Office	2,340.00	
Stationery and Printing, New York Office	647.00	
Express on Advance Copies	43.94	
		10,106.26
General:		
Library Committee	$ 3,999.99	
Membership Committee	890.55	
Finance Committee	150.00	
Standards Committee	363.41	
Code Committee	73.45	
International Engineering Congress, 1915	750.00	
Reception Committee, International Engineering Congress 1915	224.17	
Constitutional Revision Committee	695.50	
Library Research Department	250.00	
Salary and Traveling Expenses, Honorary Secretary	4,440.17	11,837.24
Total		$107,831.98
Add:		
Increase in Accounts Payable—Subject to Approval of Finance Committee, Expenses Undistributed at:		
May 1 1915, not including liability for badges sold or on hand, $70.00	$ 4,979.41	
April 30, 1916	7,146.64	2,167.23
Total Expenses		$109,999.21
Net Revenue:		$1,200.61
Profit & Loss Credits—Accessions to Library Volumes and Fixtures	$ 681.25	
Land, Building, and Endowment Fund Transferred to the General Fund	7,807.10	
Charged to Mailloux Fund on Account of Payment from General Fund in December, 1914, which should have been paid from Mailloux Fund	50.75	
Payment Received for Tickets to Annual Function, February 1915	10.50	
Adjustment of Office Furniture and Fixtures, Applicable to Prior Period	466.50	9,016.10
Gross Surplus for the Year		$ 10,216.71
Profit & Loss Charges:		
Uncollectible Dues Written Off	$ 3,403.00	
Provision for Depreciation of Furniture and Fixtures	1,267.06	
Loss on Sale of Securities	1,763.85	
Amortization of Premium on City of Wilmington, Delaware, 4½% Bonds of 1934	58.67	
Total		6,492.58
Net Surplus for the Year		$ 3,724.13
Surplus, May 1, 1915		610,288.48
Surplus, April 30, 1916		$614,012.61

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

STATEMENT OF CASH RECEIPTS AND DONATIONS FOR DESIGNATED PURPOSES. ALSO DISBURSEMENTS, FOR THE YEAR ENDED APRIL 30, 1916.

EXHIBIT C.

RECEIPTS:	
Land, Building and Endowment fund—Interest,	$104.62
Life Membership Fund—Interest,	206.63
International Electrical Congress of St. Louis Library Fund—Interest and Royalties,	97.65
Mailloux Fund—Interest	45.00
Midwinter Convention Fund	158.93
Total,	$612.83
DISBURSEMENTS:	
Land Building and Endowment Fund—Account payment of mortgage on land, 25-33 West 39th Street, New York City	$7807.10
Life Membership Fund,	269.38
Mailloux Fund,	54.95
Total,	$8131.43

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past eight years.

Year ending April 30	1909	1910	1911	1912	1913	1914	1915	1916
Membership, April 30, each year	6400	6681	7117	7459	7654	7876	8054	8212
Receipts per Member	$13.21	$13.35	$13.37	$13.19	$13.45	$14.08	$14.06	$13.62
Disbursements per Member	10.49	12.03	11.03	12.44	15.57	12.86	13.54	13.74
Credit Balance per Member	$2.72	$1.32	$2.34	$ .75	*$2.12	$1.22	$ .52	*$ .12

*Deficit.

Respectfully submitted for the Board of Directors,

F. L. HUTCHINSON, *Secretary.*

New York, May 16, 1916.